

NASA Conference Publication 2149

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Impact for the 80's

*Proceedings of a conference
held at Lewis Research Center
Cleveland, Ohio
May 14-15, 1980*

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NASA Conference Publication 2149

Impact for the 80's

Proceedings of a conference on
Selected Technology for Business and Industry
held at Lewis Research Center, Cleveland, Ohio
May 14-15, 1980



National Aeronautics
and Space Administration

**Scientific and Technical
Information Office**

1980

Foreword

This Conference, "Impact for the 80's", is intended to acquaint leaders from business and industry in Northeastern Ohio with selected technology derived from activities at the NASA Lewis Research Center.

The conference is motivated by an important objective of NASA: To ensure maximum value from national aerospace activities.

Although the civilian aerospace program is less than a penny out of the Federal budget dollar, it is a significant part of the approximately \$30 billion Federal outlay for research and development in 1980. Federal research and development expenditures represent about half of the national total outlay. Thus, it is important that our Nation use the results of these expenditures as effectively as possible. In fact, the legislation that established NASA stipulates that NASA shall "provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

Usefully disseminating the technical information being generated in our country is especially difficult because this information is so profuse, so fragmented, and so isolated from many potential users by company, industry, geography, and other factors, such as the form in which it appears. NASA has addressed itself to this communication problem in a variety of ways. This Conference is one such attempt at communication.

This Conference follows a series of conferences sponsored by Lewis for nonaerospace technical audiences: automotive industry (at SAE, Detroit, Feb. 28, 1978), gas industry (NASA SP-5102, 1975), sputtering and ion plating industry (NASA SP-5111, 1972), electric power industry (NASA SP-5057, 1968), industry and commerce (NASA TM X-52345, 1967), petroleum industry (NASA SP-5053, 1965), and local business and industry (NASA SP-5015, 1964). Major changes in the technologies addressed at Lewis since the last conference for local business and industry prompted selection of a mostly Northeastern Ohio audience. The Greater Cleveland Growth Association helped greatly by suggesting topics and assisting us in identifying the audience.

The underlying premise of this Conference is that advances made in one technical field often contribute to other fields. Examples abound in the world of technology. Based on this premise, new or emerging technologies believed to be of substantial interest or potential value to business and industrial leaders were selected for presentation.

Certain energy-related subjects that are receiving aggressive research and development attention—wind power, solar cells, and aircraft and automotive propulsion—may impact existing business and industry or may open new business and industrial opportunities; formal briefings were presented on such broad subjects. Tours of the Center taken after the formal presentations featured displays and demonstrations of useful devices and techniques in a number of areas: electrochemistry, materials, bearings, lubrication, electronics, computers, instrumentation, and measurement.

The intention is to describe advances in diverse technologies in a way that invites further inquiry. What NASA is doing and learning is, after all, yours. If additional value can be derived from the results, it should be. We want you to use whatever is useful to you.

Walter T. Olson
Director, Technology and Public Affairs
Conference Chairman

Introduction

It is my intention to introduce the Lewis Research Center and to give you an idea of the scope of our activities so that you will understand better the origins of the contents of this meeting.

We are called an energy conversion center in the broadest sense. We convert energy from one form to another: fuel to horsepower for aeronautics, ions to thrust for space, and wind to electricity for terrestrial energy. We consider ourselves the finest research and technology center in the free world to pursue that activity.

For those of you who are not acquainted with the National Aeronautics and Space Administration (NASA), it is an independent agency of the Federal government. The Administrator and the staff headquartered in Washington interface with the Office of Management and Budget and with the Congress. They advocate programs, present them to the Congress, and manage the broad programs of the agency.

The programs are implemented by ten NASA field centers and the Jet Propulsion Laboratory of the California Institute of Technology.

Five of the field centers were formerly part of the National Advisory Committee for Aeronautics (NACA): Lewis Research Center (Ohio), Langley Research Center (Virginia), and Ames Research Center (California) are the research and technology centers of the agency. Hugh L. Dryden Flight Research Center (California) supports flight research; and Wallops Flight Center (Virginia) supports small rocket launches. NASA's mission oriented centers were acquired or created when NASA was organized. They are Goddard Space Flight Center (Maryland) mostly for space science, Lyndon B. Johnson Space Center (Texas) for manned spacecraft, John F. Kennedy Space Center (Florida) for launchings, George C. Marshall Space Flight Center for large launch vehicles, the smaller National Space Technology Laboratories (Mississippi) for testing rocket engines, and the Jet Propulsion Laboratory (California) for planetary studies. Among the centers, there is, of course, some interlocking of roles and missions.

Our job at Lewis is to work with industry and universities as a team, develop the research and technology base, transfer the technology to industry for commercialization or to a mission-oriented center, and then back away gracefully to seek bigger dragons to conquer. We have been doing that for many years in the aeronautics business. We are now doing it for propulsion in the automotive business.

The NASA Lewis Research Center occupies 350 acres beside the Cleveland-Hopkins Airport and 8000 acres at Sandusky (about 60 miles west of Cleveland) where we have some larger research facilities, including an experimental wind turbine, and storage facilities.

Lewis, then called the Aircraft Engine Research Laboratory (AERL), was formed in 1941 as an expansion of the powerplants work of the NACA Langley Laboratory. AERL contributed to our military air superiority during World War II. In the 1940's and 1950's researchers here developed many of the features still seen on today's gas turbine engines. We still have close relations with the Department of Defense, even though most of our activities are commercially oriented; the requirements of military engines are quite different from those of commercial engines. Also in the 1940's and 1950's, we built major propulsion test facilities, which are still active. We are very proud of our plant.

In 1948 the Center was renamed the NACA Lewis Flight Propulsion Laboratory. In 1958 it was again renamed the NASA Lewis Research Center after which the Center role was expanded, mainly to exploit for the space program the technologies that we had developed over the years. But aeronautical propulsion research and technology is still one of our bread and butter items, and we continue to be very active in that area.

As a part of NASA, the space agency, we have greatly expanded chemical rocket and electric propulsion technology. We developed space power technology, and, in part because of that expertise, we are now developing technology for terrestrial power systems for the Department of Energy.

Basic and applied materials research, especially in the high-temperature area, has become a center of excellence here at Lewis. Some of that activity is described at this conference. The study of high-

energy rocket propellants, including hydrogen, was pioneered here at Lewis. Of course, that opened up new vistas.

We have had management responsibility for medium-class launch vehicles, specifically, Atlas, Agena, Atlas-Centaur, and Titan-Centaur. The Atlas-Centaur will continue to be the workhorse for medium-size payloads until the Space Shuttle becomes operational, at which time Atlas-Centaur will be phased out.

Recently we were designated as NASA's center for space communications research and technology. That assignment came because of our electronics expertise with instrumentation and data gathering on various engines and our experience with the Communications Technology Satellite in the 12- to 14-gigahertz band. That assignment is new and next year when you come back, or the year after, you will see some big antennas here at Lewis; we are now involved in high-frequency research in the 20 to 30 gigahertz area.

The Congress amended the National Aeronautics and Space Act of 1958 to authorize NASA to work in terrestrial energy, where national needs are so acute. At this conference we will describe to you our studies on the Stirling and gas turbine engines for automobiles. Again, we work with industry as a team—Ford Motor, Chrysler, General Motors. Our objective is to develop the technology base and then back away. Those companies are accustomed to looking at government as a regulator. They are very pleased that NASA is not such an organization, and we are developing a very fine rapport, although it has taken a little doing.

We manage the Department of Energy's program for large wind turbines, which started in 1975 with an experimental wind turbine at Plum Brook—a 100-kilowatt machine that we still use for testing new techniques. We develop and install stand-alone photovoltaic systems, including energy generation, storage, and distribution. For example, the Papago Indian village of Schuchuli, Arizona, now has lighting, refrigeration, sewing machines, and pumped water—all made possible by a Lewis-supplied solar cell system. So too, a village in Upper Volta, Africa, at the request of the State Department.

Among other topics of research and development are hydrodynamics, and coal cogeneration—a process intended to convert dirty, high sulfur, Ohio coal to electricity without pollution.

In aeronautics, Lewis' work ranges from studies on basic processes like fluid flow and combustion through components like compressors and turbines to full-scale systems. Although we do not develop engines at Lewis, we do use engines as a research tool. For example, the F100 engine is used in one of our test cells to study control techniques, where inlet area, compressor blade angle, fuel flow, rotor speed, and exhaust nozzle area all vary as functions of altitude and flight speed.

We conduct propeller research for general aviation aircraft. Recently we developed an energy efficient propeller that is 80 percent efficient at Mach 0.8, for about a 33 percent improvement in fuel consumption. Because of the emphasis on energy conservation, the concept of a high-speed, advanced turboprop is of interest to the airlines and the aircraft industry in general; we are pursuing that concept.

In space propulsion we are working on advanced engines that will take spacecraft from near-Earth orbit to geosynchronous orbit. Electric thruster technology is at the point where we are transferring it to the Marshall Center so that they can develop a Space Electric Propulsion System using ten of these thrusters for planetary missions.

Also, we are actively pursuing low-thrust chemical rockets. One application of such rockets is in space propulsion systems to help construct big antennas in space for communications and air traffic control.

In space power research and technology we are the Center for solar cell development for NASA. We are looking at gallium arsenide cells as well as at advanced techniques for silicon cells. We develop all the batteries for space applications for NASA. We have concentrated on silver-zinc, and some of our techniques have been transferred to nickel-zinc batteries that are now being pursued both by industry and the Department of Energy. We do all the fuel cell work for space. That technology, too, has been transferred to terrestrial applications.

We are now in the process of finishing studies that define the communications market, and we have concluded that the present frequencies, which include 14 to 16 gigahertz and lower, will be saturated in the mid-1980's. In order to create a new capability, we are looking at the 20 to 30 gigahertz range, which involves a new body of technology.

We are now in the process of defining what communications demonstration experiments are required and what key technology developments are required. We will design and build at least one and probably two satellites, launch them in about 1986 to 1988, and control them from Lewis. The intent is to put all the complicated equipment in the satellites and use very low-cost ground terminals. Eventually we will have antennas that can be fitted into a small suitcase. Such a multibeam satellite will service all the United States, including Alaska, Hawaii, and Puerto Rico.

In the terrestrial energy business we are very careful to pick technologies that are synergistic to our mainstream aeronautics and space effort. We do about \$150 million dollars a year of work for the Department of Energy.

We have two big gas turbine development projects for the automotive propulsion business: one with AirResearch and Ford and one with Detroit Diesel Allison and Pontiac. The government puts up the high-risk front-end money and eventually the automotive industry will share the cost as we go downstream. We think we can obtain a 20 to 30 percent improvement in fuel consumption with virtually no pollution. The question is whether this can be done economically and with all the "ilities": reliability, maintainability, producibility, and so forth.

I keep emphasizing that we work with industry as a team to develop the concepts and then back away gracefully.

We work very closely with the universities, as well as with industry. We make research grants to universities. We have a cooperative program where faculty members are in residence here, especially during the summer. We have co-op students. In fact, we have many joint programs for basic research.

And of course, we work with other government agencies, for example, the Department of Energy, the Department of Defense, and the Coast Guard. For instance, we have developed a radar device that measures the extent and thickness of the ice on the Great Lakes. We have transferred the system to the Coast Guard. With the ice information the device provides, the Coast Guard produces daily ice charts that permit navigation all year.

NASA expenditures are modest; in fact, we get only eight-tenths of 1 percent of the U.S. dollar. The largest outlays in the Federal budget are for direct benefit payments to individuals. Incidentally, in the last two decades, this item has gone up from 24 percent to 43 percent and is still rising; national defense has decreased from about 50 percent to 24 percent. NASA's budget is less than one-tenth of what you pay as interest on the Federal debt.

The Lewis budget for fiscal year 1981 is about \$525 million. Three-fourths of this money goes directly to research and development, about 80 percent of it performed out-of-house; almost one-fourth is civil service salaries, utilities, guards, cutting the grass—keeping the plant going. About 2 percent is for new facilities and major rehabilitation of old facilities.

The research and development dollar split is about one-third each: aeronautics, space, and energy. Our manpower split is quite different; about two-thirds of our staff is devoted to aeronautics. We consciously limit the staff associated with energy programs so that we can keep our aeronautics and space role consistent with the personnel ceiling of 2835 persons imposed by the Office of Management and Budget through NASA Headquarters.

At Lewis over half of the staff are scientists and engineers. Thus we are a very high technology center. They are supported by over 1000 skilled craftsmen, technicians, and big facility operators, and by some 300 very fine administrative professionals.

We operate in a matrix fashion. Project offices in aeronautics, space, and energy receive support from the other parts of the organization. For example, the Automotive Gas Turbine Project Office is located in the Energy Directorate. It receives science and technology skills from the Science and Technology Directorate, for example, materials, bearings, seals, transmission, compressors, turbines, combustion. It receives computer services from the Engineering Services Directorate. From

the Technical Service Directorate, it receives test installation service, technicians, and related services. And from the Administrative Directorate, procurement services, photographic services, and so forth. The aeronautics, space, and energy directorates are responsible for advocacy, planning, work breakdown structure, and definition of the tasks.

The science and technology people not only support the projects, but they are also responsible for maintaining expertise in their own disciplines. The three support organizations are Administration, Engineering Services, which includes computing, engineering drafting, facility support, and design services, and Technical Services for technicians and craftsmen.

Our investment cost in building and facilities is over \$300 million in 1950-1960 dollars; thus the estimated replacement cost is well over one billion dollars.

This has been a very brief introduction to Lewis. Let me encourage you to maintain relations with our organization. I think you will be surprised at the breadth of our activities and the expertise of our staff.

John F. McCarthy, Jr.
Director
NASA Lewis Research Center

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Energy Overview

Henry O. Slone

National Aeronautics and Space Administration

Lewis Research Center

Cleveland, Ohio

There is no doubt that the energy problems facing our country and the world are the least understood and the most complex and challenging problems that our Nation has ever faced. The solutions will require the best efforts of all facets of the American system: Government, business, industry, the university community, and, indeed, every one of us.

In this paper attention is focused on how NASA Lewis is using its experience, capabilities, and facilities in support of energy programs being conducted by the Department of Energy (DOE) and other agencies. First, however, some background information is presented regarding NASA's involvement in solving some of our energy problems. Then our energy technology effort here at NASA Lewis is briefly reviewed. Subsequent papers give more detail on specific energy projects at Lewis.

NASA's energy technology objective is to apply our knowledge in aeronautics and space technology, our management expertise, and our facilities to the research and development needs of the DOE and other agencies. The NASA Centers involved are the Lewis Research Center, the Marshall Space Flight Center, and the Jet Propulsion Laboratory. An obvious question is, Why and how is the Space Agency involved in solving ground-based energy problems? NASA energy involvement is mandated by Congress and needed by DOE. Starting with the OPEC oil embargo in 1973-74 Congress has passed a number of energy bills, and, since in the eyes of Congress NASA was and is a *can-do agency*, NASA participation was written into many of the bills and the National Aeronautics and Space Act was amended three times: in 1974 by the Solar Energy, Resources, Development & Demonstration Act, in 1976 by the Electric & Hybrid Vehicle R&D Act, and in 1978 by the Automotive Propulsion R&D Act. Currently the basic working relationship between DOE and NASA is guided by the Memorandum of Understanding signed by both agencies in June 1975, which states that "it is the policy of DOE and NASA to identify specific program tasks which can be undertaken by the NASA Centers in support of DOE programs to the benefit of both agencies and the Nation."

The NASA activities in support of the National Energy Research, Development, and Demonstration (RD&D) program consist of reimbursable programs conducted by NASA for other agencies and NASA-funded programs. In this regard, NASA Lewis is reimbursed by three agencies: the Department of Energy, the Department of Interior, and the Agency for International Development. NASA funds (seed money) are specifically used to investigate the application of existing in-house capabilities to attacking a given energy-related problem. If the investigation proves to be successful, a plan to solve the problem is developed and submitted to the agency having cognizance over the particular energy area. If the agency accepts the plan, a transfer of funds takes place and a reimbursable project is then undertaken. Total reimbursable energy funding transferred to NASA this fiscal year by DOE and other agencies was about \$250 million, of which Lewis received about \$130 million. About 95 percent of the funding was from DOE.

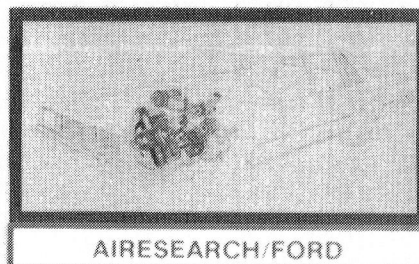
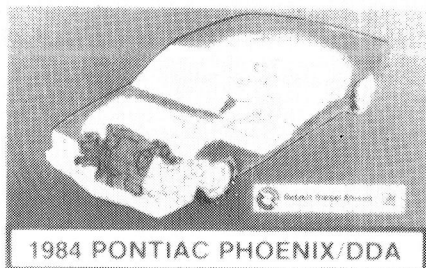
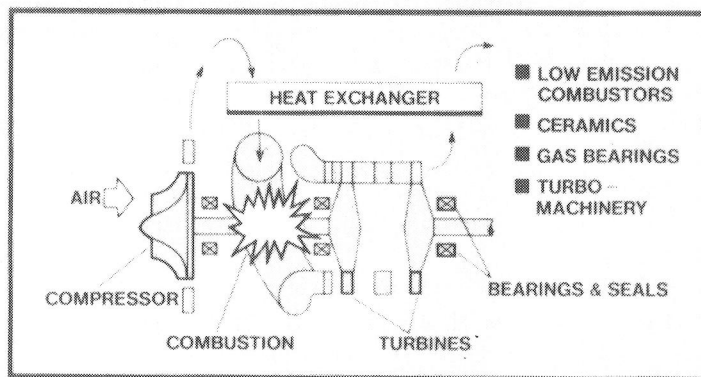
It is the objective of the DOE-NASA energy program to ensure that U.S. Government-developed technology is available to all U.S. industries. One way this is done is by involving industries in programs as participants. About 85 percent of our funding is spent on outside contracts and grants.

We also document the technology developments and disseminate the documented material in technical meetings, conferences, and workshops. An example of the workshops NASA conducts was the one held on May 14, 1980, in Tuscon, Arizona—the National Conference on Photovoltaic Opportunities for Electrically Powered Products. The presentations and discussions during the workshop covered practical information about solar photovoltaics and their application to commercial products as well as existing and potential domestic and international markets for photovoltaic-powered products. Since the early 1970's, NASA Lewis has been utilizing its many and unique capabilities that were developed to solve aeronautics and space problems to make meaningful contributions to solving certain energy problems. Lewis is the only power and propulsion technology center in the U.S. Government. There are major “in-place” energy-related technologies such as materials and metallurgy, combustion, lubrication and wear, bearings and engine seals, compressors and turbines, magnetohydrodynamics, electrochemistry, photovoltaics (solar cells), thermodynamics, heat transfer, system dynamics, and system analysis. The current energy activities at Lewis are in two broad areas—automotive propulsion systems technology and stationary power. These activities could also be described in terms of conservation of energy (propulsion system technology), switch to coal (stationary-power energy conversion), and new energy sources (wind, photovoltaics). A brief overview of our major energy activities is given here.

Automotive Propulsion Systems Technology

As a result of Congressional legislation, the DOE has implemented a program, to significantly reduce the Nation's dependence on petroleum, that may result in an alternative automotive engine in the 1990's with high fuel economy and clean exhaust. The goal of this program, for which NASA Lewis has project management responsibility, is to provide the technology base within the automobile industry to support production development of alternative automotive engines that show

AUTOMOTIVE GAS TURBINE



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Figure 1

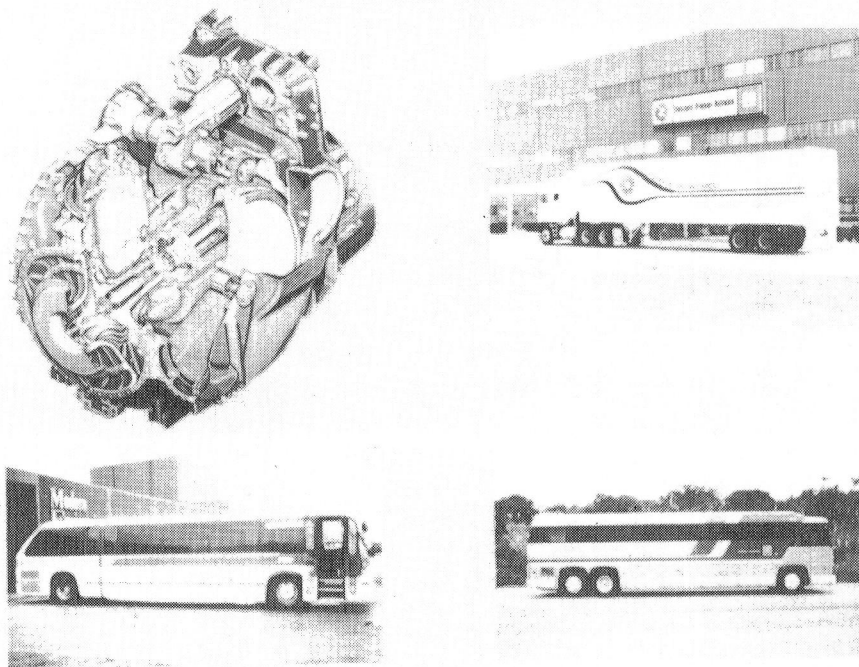
at least 30-percent improvement in fuel economy over future spark ignition internal combustion engines; that meet emission standards; that can use petroleum, nonpetroleum, or blends of fuels; and that can be sold competitively. Two external combustion engines, the gas turbine and the Stirling engine, show promise for meeting this goal. It is hoped that at the end of this Government/industry effort, in the mid-1980's, the automotive industry can make a decision to proceed into production engineering with either the gas turbine or the Stirling engine, or both. Two cost-sharing contracts for gas turbine engine development (fig. 1) were awarded in October 1979 to two teams: General Motors (Detroit Diesel Allison and Pontiac) and AiResearch/Ford. These two 6-year contracts are funded at about \$60 million each. There is more discussion of this effort in M. H. Krasner's paper.

Another aspect of gas turbine engine development, shown in figure 2, is a demonstration effort to support the commercialization of gas turbine technologies. Five gas-turbine, intercity transit buses will soon be in revenue service in the City of Baltimore, and four intercity Greyhound buses are in revenue service out of Washington. Also shown is a gas-turbine-powered truck that is driven for demonstration purposes only. In each case the gas turbine engines are being compared in performance and reliability with the diesel engines that had powered the buses and the truck.

One cost-sharing contract, valued at about \$90 million, was awarded to the team of Mechanical Technology Incorporated/United Stirling of Sweden/American Motors General for development of a Stirling automotive engine (fig. 3). Shown is a Stirling engine in an American Motors Spirit that is used for demonstration. Once again, more about this engine is given in Krasner's paper.

In September 1976, Congress passed the Electric and Hybrid Vehicle Research, Development, and Demonstration Act, which DOE is implementing and for which we are providing support in propulsion system research and development. The overall goal of this important program is to accelerate the commercialization of vehicles that use electricity as the principal source of propulsion energy and thus to provide fuel flexibility for the transportation sector. The research and development goal is to advance electric and hybrid vehicle technology to improve cost effectiveness, performance, and reliability. Propulsion systems are the responsibility of the Lewis Research Center;

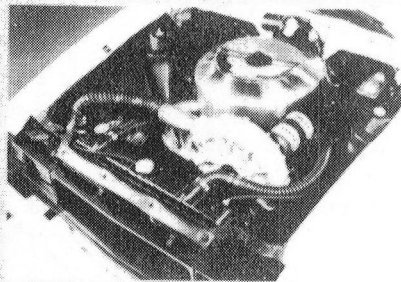
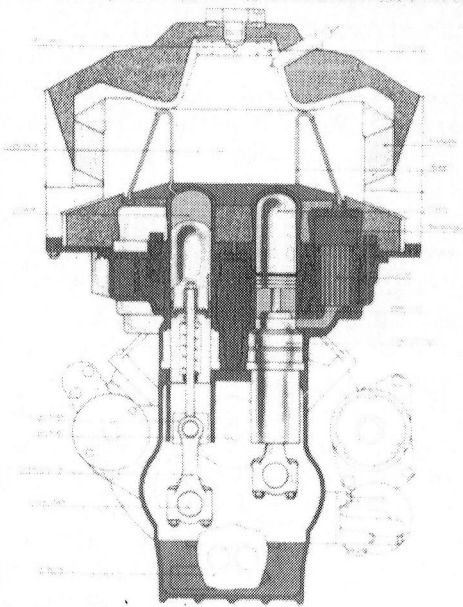
BUS/TRUCK GAS TURBINE R&T



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Figure 2

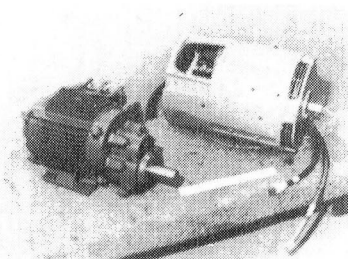
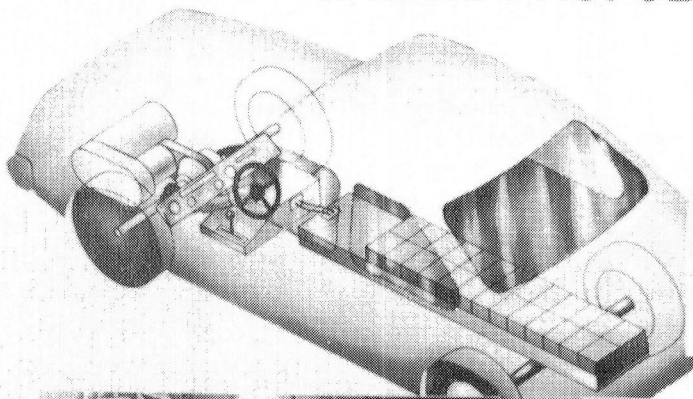
STIRLING CYCLE ENGINES



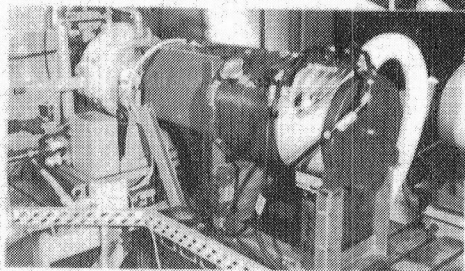
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Figure 3

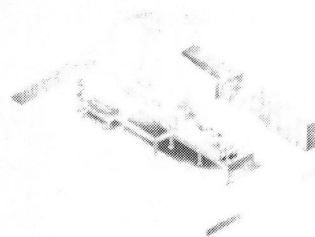
ELECTRIC VEHICLE PROPULSION R&T



ELECTRIC VEHICLE MOTORS



MOTOR and CONTROLLER



ROAD LOAD SIMULATOR

Figure 4

vehicle systems, of the Jet Propulsion Laboratory; and batteries, of ANL. Some of our propulsion system activity here at Lewis is shown in figure 4. There is further discussion of this program in H. J. Schwartz's paper on electric vehicles.

Stationary-Power Conversion

Wind and Solar Energy

It is becoming generally recognized that wind energy will be the first of the solar electric technologies under development to emerge for serious consideration as a utility power generation source. The goals of the DOE Federal Wind Energy program, which started in 1973, are to accelerate the development, commercialization, and utilization of reliable and economically viable wind energy systems, to make wind energy a viable technological alternative to other forms of energy, to pursue a course that will result in the production of significant amounts of electricity, and to create a competitive industry that produces wind turbines. NASA Lewis has project management responsibility for large, horizontal-axis wind turbines and the associated supporting research and technology. Figures 5 and 6 show the size and location of some of the large wind turbines managed by Lewis. The rotors of these machines turn at about 35 to 40 revolutions per minute (rpm), operate in winds between 8 and 35 mph, and provide enough power for about 500 average homes (Mod-1) or 100 average homes (Mod-0A). The Mod-0A at Clayton, New Mexico, has been operating since early 1978; and the Mod-1 at Boone, North Carolina, began its initial rotation in the summer of 1979. Another Mod-0A machine began operation in Hawaii in May 1980. The Mod-2 will begin operation later in this year in the state of Washington. Wind power commercialization is discussed in W. H. Robbin's paper.

Lewis is also managing a program for the Department of Interior wherein a megawatt-size wind turbine will be operated in conjunction with a hydroelectric dam (for storage) in Wyoming.

LARGE WIND TURBINES

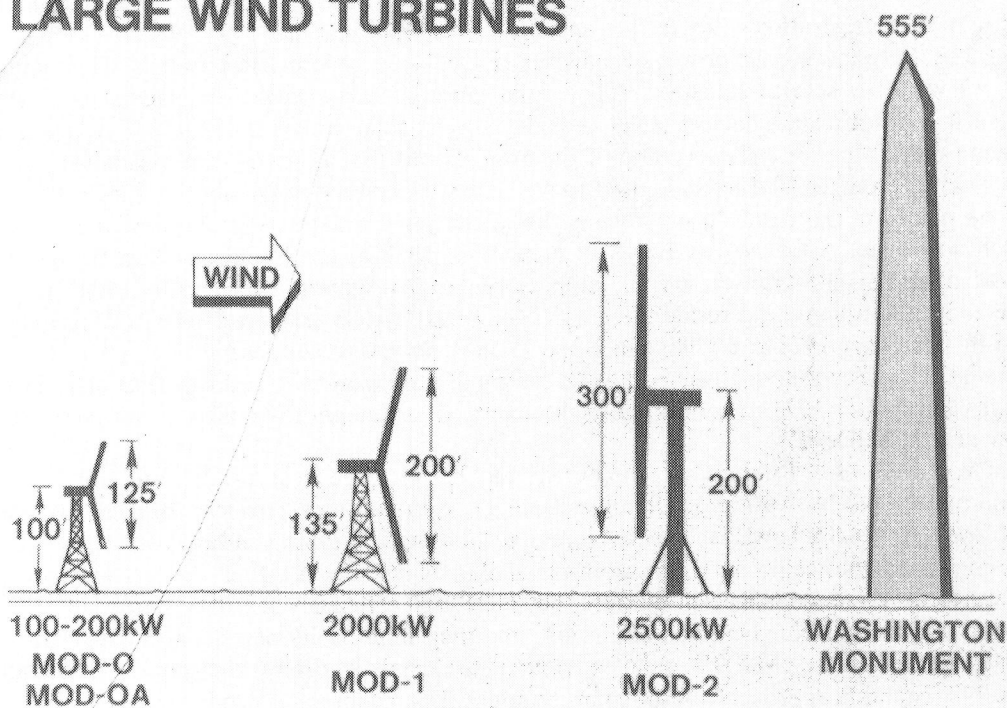


Figure 5

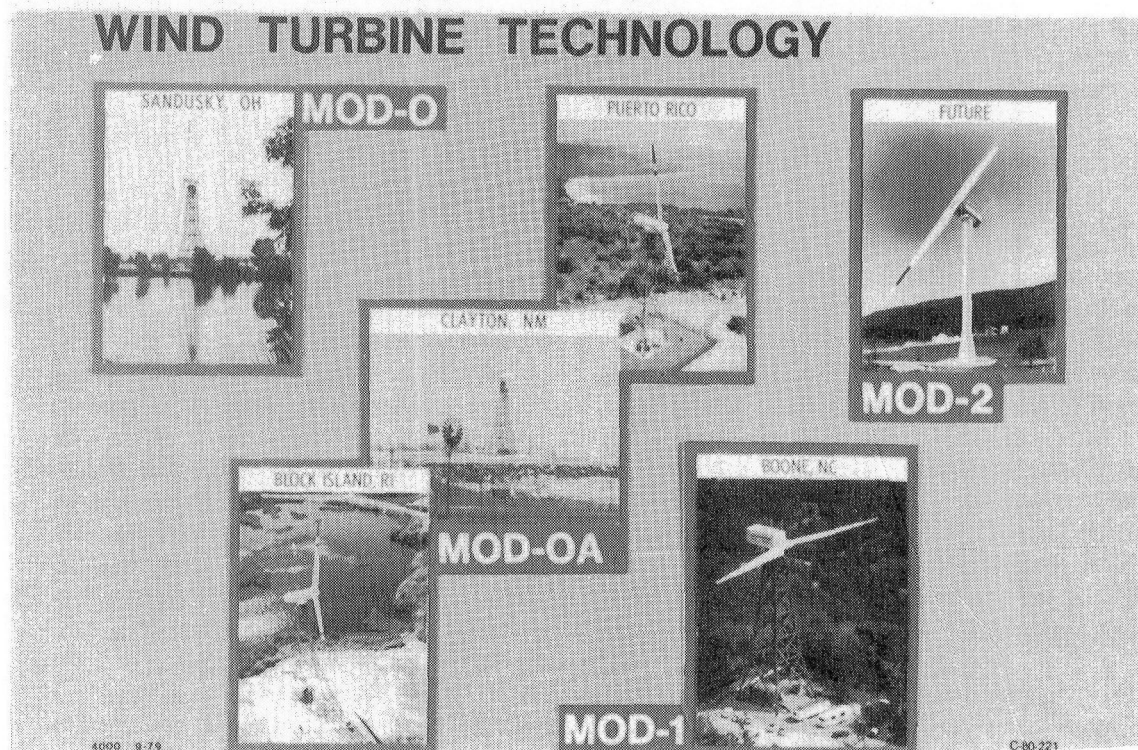


Figure 6

NASA Lewis solar photovoltaic activities are funded by DOE and the Agency for International Development (AID). These projects are to demonstrate in the field that photovoltaic power systems are suitable and ready for specific near-term applications such as village power systems, water pumping, irrigation, refrigeration of medicines and food, and lighting. Since 1976, NASA Lewis has installed over 35 solar photovoltaic power systems for various applications and power levels ranging from about 50 watts to several kilowatts. (The solar photovoltaic conversion process uses the photovoltaic effect in solid-state devices (solar cells) to convert solar energy directly into electricity, with no moving parts.) Figure 7 shows some of the applications that Lewis is responsible for. The System Test Facility, located at Lewis, is used to test solar arrays and solar photovoltaic systems before they are placed in the field. Also shown is the world's first village solar photovoltaic power system, which was installed by NASA Lewis in November 1978 at the Papago Indian village of Schuchuli, Arizona. This 3.5-kilowatt system supplies power for lighting, refrigeration, and water pumping for about 95 Indians who reside there. A 1.8-kilowatt system (as part of our AID project) was installed in December 1978 at a village in Upper Volta, Africa, to supply power to grind grain and pump water. The fire lookout tower in Lassen National Forest and the highway dust sign have been operating since early 1977. There is more discussion of solar photovoltaics in the paper by R. G. Forney and J. N. Deyo.

As some of you are aware, Public Law 95-620 requires that most Federal installations stop using petroleum and natural gas by 1990. Also, in all probability, many utilities currently using petroleum will switch to coal. At NASA Lewis we are developing technology along with industry for the use of coal to fuel coal-fired fuel cells, MHD generators, and turbines (fig. 8). Fuel cell systems offer attractive features for commercialization because they have high efficiency at full or part load, they are clean and quiet, they provide heat and electricity, and their modularity permits multikilowatt to multimegawatt power levels. MHD's chief attributes are that it offers the potential of an environmentally acceptable approach to using our abundant coal resources to produce electric power at very high efficiency (e.g., a potential 50 percent improvement over current steam plants) and attractive costs. The heat engine effort is directed toward advancing the technology for gas turbines,

PHOTOVOLTAICS TECHNOLOGY

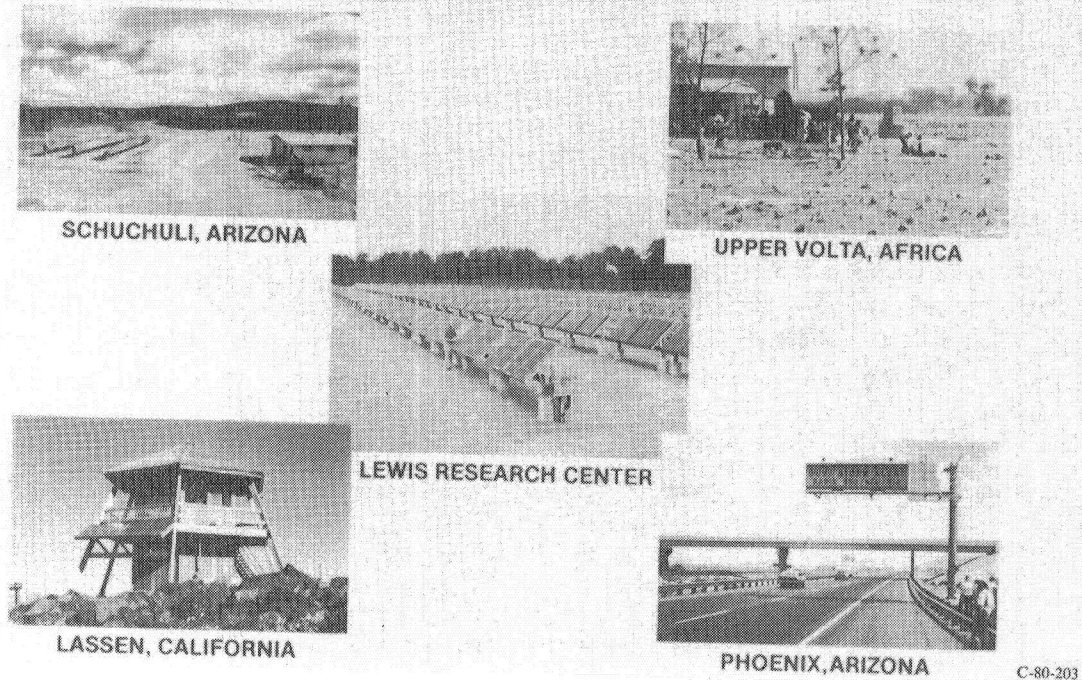


Figure 7

STATIONARY POWER GENERATION

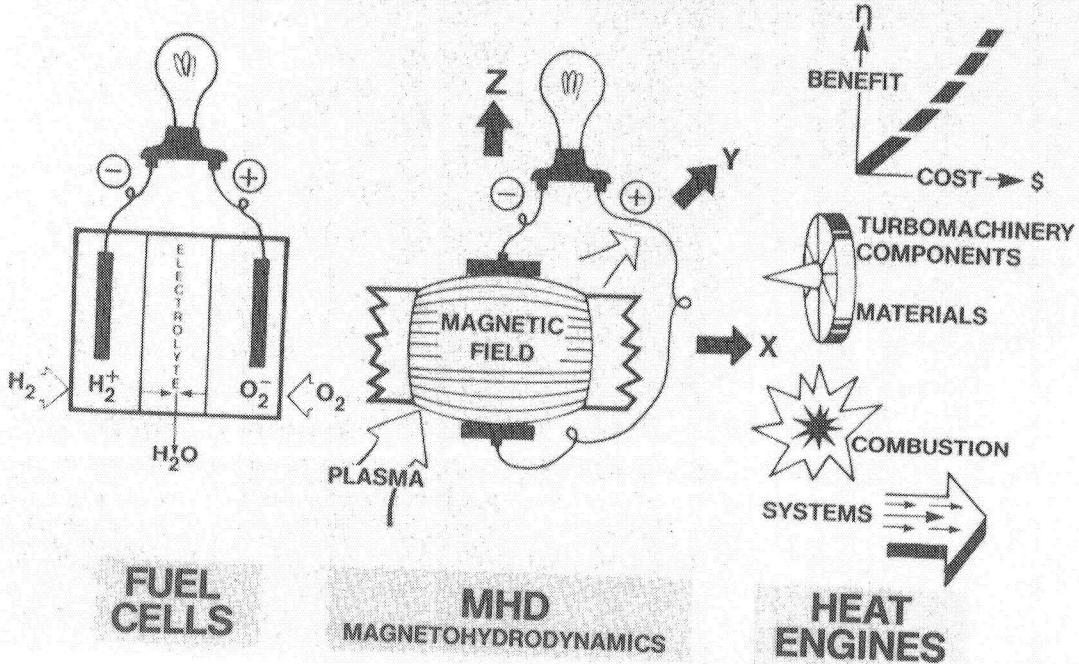
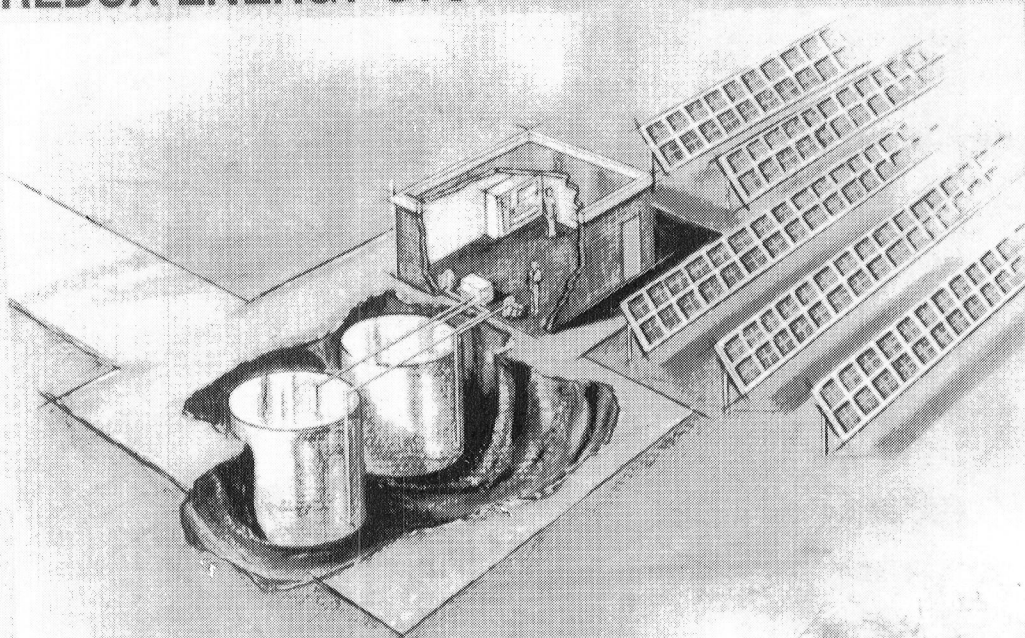


Figure 8

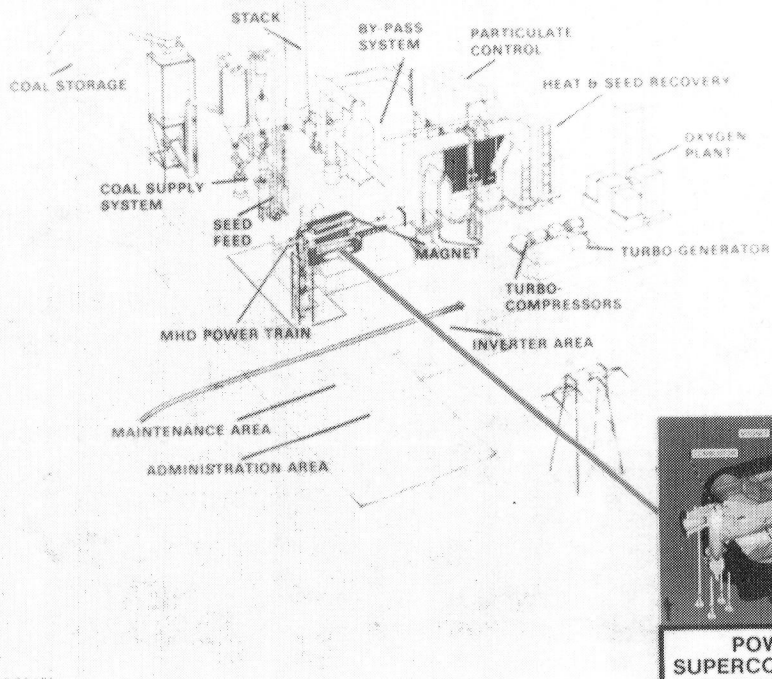
REDOX ENERGY STORAGE SYSTEM



C-80-237

Figure 9

MHD ENGINEERING TEST FACILITY



C-80-181
4000 3-60

Figure 10

so that they can be used with coal or coal-derived fuels. The objectives of these three projects are

(1) For fuel cells—to develop commercially viable phosphoric acid fuel-cell systems for electric utility power generation and on-site/integrated energy systems for residential, commercial, and industrial applications.

(2) For magnetohydrodynamics (MHD)—to develop advanced MHD power train technology and to define the design of a commercial prototype plant (engineering test facility) directed toward determining the commercial viability of coal-fired MHD powerplants having potential for high plant efficiency and low cost of electricity.

(3) For heat engines—to do system studies and to develop near-term combustion and materials technology for turbine powerplants in order to shift from natural gas and oil to coal and coal-derived fuels. Figure 9 shows an on-site commercial application for a fuel cell, and figure 10 shows the MHD engineering test facility that is planned to demonstrate the feasibility of MHD for a utility application. Unique MHD systems are the power train, the magnet, and the heat and seed recovery system. (MHD is a process in which fuel is heated to such a high temperature that it becomes ionized. By passing this high-temperature gas through a channel surrounded by strong magnets, the electrons in the gas can be collected, thus yielding electrical energy.) The paper by L. I. Shure discusses a unique concept for burning Ohio high-sulfur coal here at Lewis.

Energy Storage

Energy storage is an essential element to many energy conversion systems. For example, solar energy must be stored when the Sun is not shining and wind energy when the wind is not blowing. One interesting and promising concept of energy storage, conceived here at Lewis in 1973 and currently being evaluated, is shown in figure 11. Redox is an acronym which stands for reduction oxidation. Chemical energy is converted into electrical energy when two reactant fluids—chromium chloride and iron chloride—interact through a thin membrane. There is further discussion of this system by L. H. Thaller.

This paper briefly touched on NASA's involvement, especially here at Lewis, in solving our energy problems.

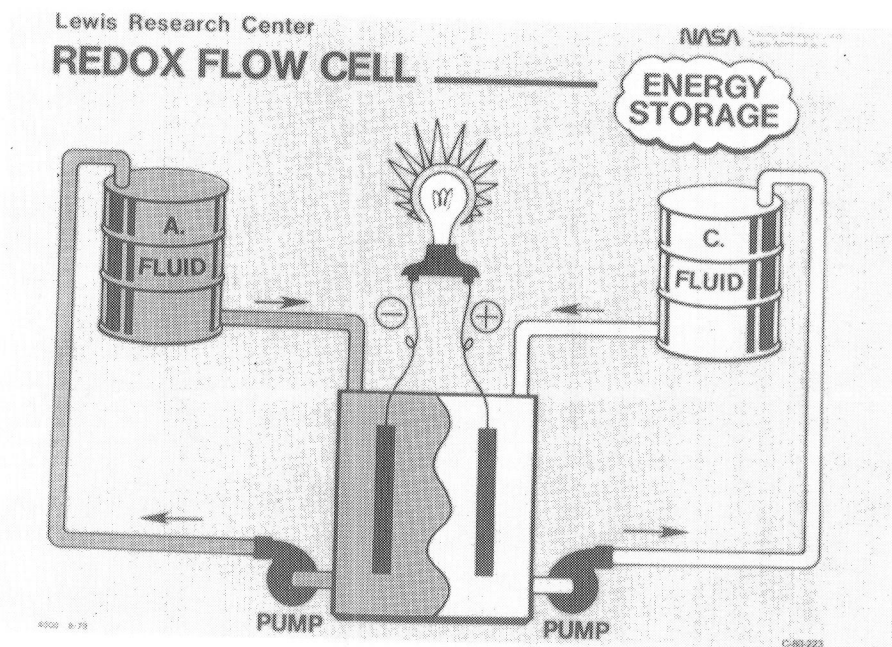


Figure 11

NASA Research in Aeropropulsion

Warner L. Stewart
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Cleveland, Ohio*

In 1941 when the Lewis Research Center started it was dedicated solely toward research in aeronautical propulsion. Even now, with new responsibilities in space and energy research, about half of the Center's effort is applied in that area, principally because of the unique expertise and facilities that are available here.

The programs at Lewis are consistent with the charter of NASA in aeronautics, which is directed toward three objectives: First, helping to maintain a safe, economically viable, environmentally acceptable air transportation system including both commercial transports and general aviation aircraft; second, to help maintain a strong industrial competitive posture on the international scene; and finally, to help maintain a strong military posture (for all three services, Air Force, Navy, and Army).

The role of Lewis in aeronautical propulsion is, of course, to advance the state of the art in the engine systems and components themselves, as well as to help solve some of the new problems that are confronting the civil and military aeronautic sectors. This paper reviews some of the programs that are under way, with emphasis on the future needs and opportunities in aeronautics.

Commercial Aircraft

Consider first the familiar subsonic airliner, such as the Boeing 707 shown in figure 1. This kind of vehicle is the backbone of our commercial aircraft aviation sector. The transportation system enabled by these aircraft has affected the way business is conducted and, indeed, influenced the shape of our total contemporary society.

The airline industry is a healthy one. However, there have been and are many problems plaguing it. The major current concerns are environment and fuel. In the environmental area exhaust emissions

SUBSONIC AIRLINER

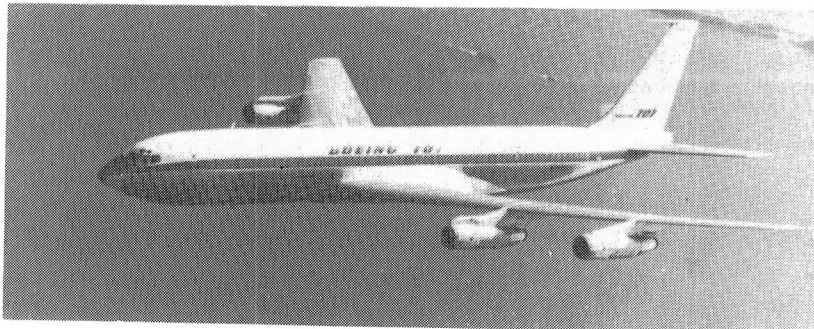


Figure 1

control has long been a major concern. However, there has been much progress, and at present it is not considered a critical factor. In fact, emissions by aircraft are a very small factor in the context of the total pollution scene within the country. On the other hand, the noise generated by aircraft is not so easily dismissed.

The problem of aircraft noise has been with the commercial sector for quite awhile. Increasingly militant objections are being expressed by the affected citizens. These objections have, to some extent, limited the growth of the civil aviation sector and are expected to continue as a major influence: Some communities have set curfews on airports at night. Others have disallowed the building of new airports. Because of efforts like these commercial investment in new aircraft that could emerge, such as dedicated airfreighters, has been discouraged.

In response to this problem, NASA has had numerous programs aimed at reducing the noise generated by airplane engines. For example, several years back the so-called Refan program was conducted to show how an existing commercial engine (in this case it was the JT8D, which powers the 727, 737, and DC9 airplanes) could be quieted by modifying the fan and by incorporating sound-absorbing material within the flow ducts. Figure 2 is a picture of the modified engine on a test stand. This program went through a flight activity with MacDonnell Douglas, using a DC9 with refanned engines provided by Pratt & Whitney (fig. 3). The results showed that the noise level could be reduced dramatically by this technique.

In fact, this technology is now being applied commercially in the form of the DC9 Super 80 by MacDonnell Douglas (fig. 4). More than 100 orders have been received for this aircraft, which is substantially quieter than its predecessors. It uses a derivative of the Refan engine that is being produced by Pratt & Whitney.

Many other programs are underway as part of NASA's continuing effort to develop technology that will aid in further reducing the aircraft noise.



Figure 2

FIRST FLIGHT OF DC-9 REFAN AIRPLANE



C-75-993
C/Nr 73024

Figure 3

THE MCDONNELL DOUGLAS DC-9 SUPER 80



Figure 4

NASA recognized sometime back that the high cost and limited availability of fuel represent critical threats to the viability of the commercial air transportation industry. One approach being studied is to modify the engines so that they can utilize fuels whose properties are not so tightly specified. This would broaden the sources of supply, possibly even including nonpetroleum sources such as shale oil or coal. But the major thrust of the NASA program is to reduce the consumption of fuel by the engines. The principal activity in this area, known as the ACEE (Aircraft Energy

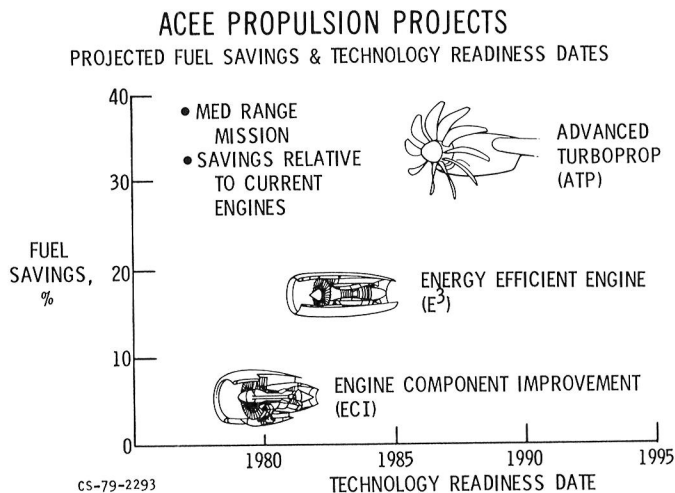


Figure 5

Efficiency) Program, was started about 4 years ago and is directed at possibly cutting the fuel use of these transports by a factor of two. There are three major propulsion parts of that program (as indicated in fig. 5). The near-term activity is called the Engine Component Improvement Program (ECI) and is directed at derivative versions of the present generation of engines. The Energy Efficient Engine is a midterm program with perhaps as much as an 18 percent fuel saving. The long-term program promises a fuel saving as much as 30 percent or more with an Advanced Turboprop. The cited fuel savings are relative to current engines installed in subsonic aircraft and flying on a midrange mission.

The near-term ECI program (fig. 6) involves three engines manufactured by Pratt & Whitney and by General Electric, who provide the majority of the engines for subsonic transports. The engines are the JT8D, JT9D, and CF6, the latter two being the engines that power the large wide-bodied jets. The objective here is to make modifications within the engine that do not represent major changes in the design but that could reduce the fuel consumption by up to 5 percent (which is highly significant to the airline operators). Example techniques include tightening up the clearances within rotating parts, reducing the amount of cooling air, and modifying the design of some components to improve efficiency. This program is nearing a close and has been deemed by the total industry, including the

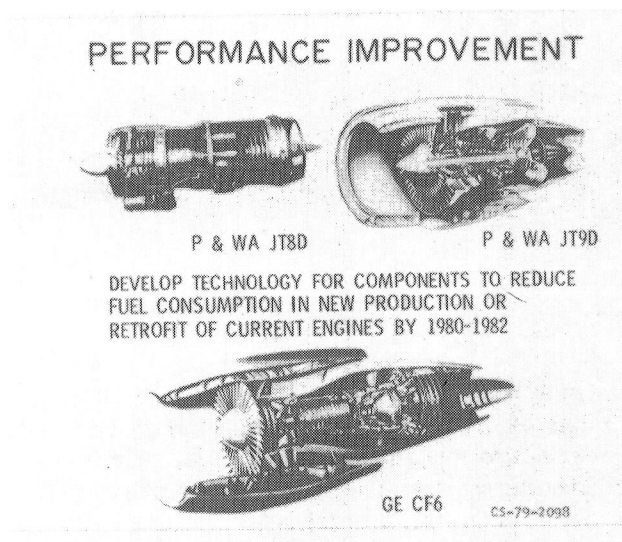


Figure 6

airlines, the engine manufacturers, and the airframe manufacturers, to be highly successful. Many of the concepts that were identified and explored in this program already are being incorporated into the production engines.

The midterm program is the Energy Efficient Engine. These are major contract efforts with both Pratt & Whitney and General Electric. The total program is about \$200 million. It involves laying out the technology for the next generation of engines that would be developed in the mid to late 1980's. The techniques that provide the potential of attaining the 18 percent fuel reduction as compared with present engines are multifold. They include higher cycle pressures (as high as 40 atmospheres, compared with 20 to 30 atmospheres in present engines), substantially improved components, higher temperature hot-end components, such additional components as mixers, ample use of composites throughout the engines, advanced control systems which will allow the engine to be tuned throughout its flight path, and the like. Figure 7 shows the engine designs that have evolved. This five-year program is presently at its midpoint. Progress to date has been very satisfactory.

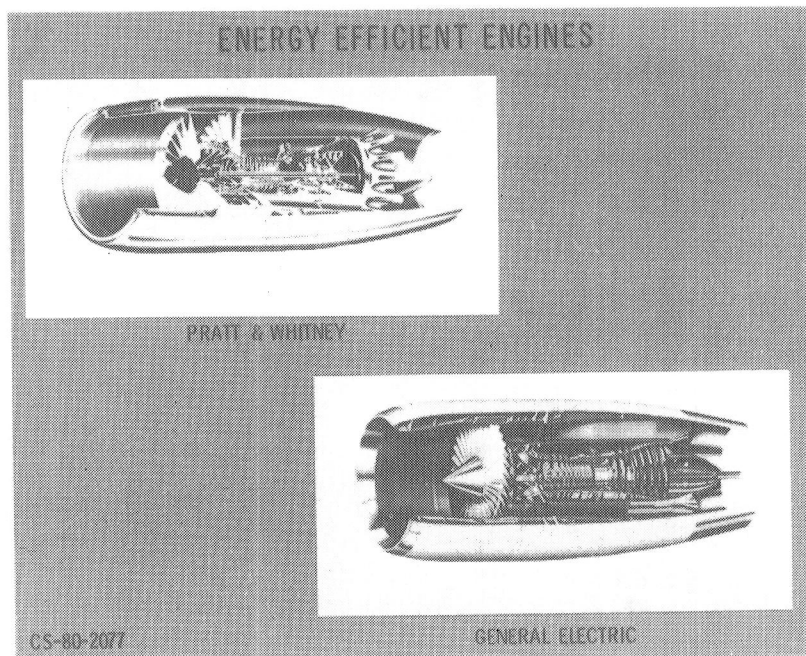


Figure 7

The third element, which is the long-term, high-risk program, is the Advanced Turboprop. The objective here is to explore what one might be able to do by going back to propeller systems, which have a much-improved propulsive efficiency compared with turbofan systems. The principal challenge is to develop the technology that might allow such propeller systems to be utilized in an aircraft that could operate in the same altitude and speed range as present subsonic jets. The type of propeller required to provide this capability is quite different from those of the past (fig. 8). Noteworthy is the large number of blades used so that the diameter is moderate, despite the low air density at high altitudes. The blades are very thin and are highly swept. This sweep is used to maintain a high efficiency in the tip region where local Mach numbers become supersonic. It also serves to lower the cabin noise level, as propellers are inherently noisy from a passenger standpoint.

The initial phases of this program have established that the aerodynamic performance of the blades is quite acceptable. However, there are still many problems of structures and aeroelasticity that must be addressed in larger sizes. The model shown in figure 8 is only 2 feet in diameter, whereas the full-scale propellers would be in the 10- to 15-foot range.

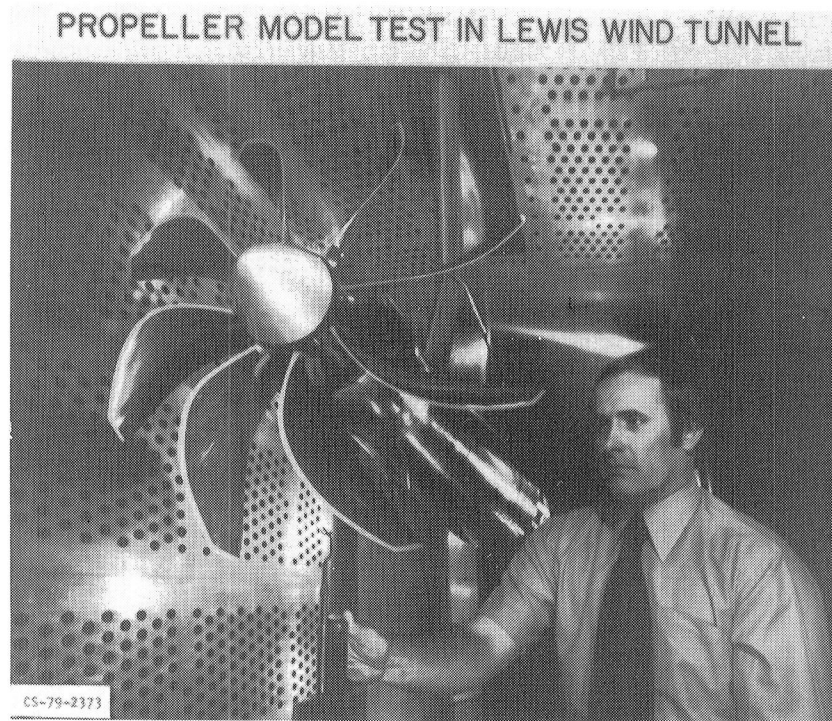


Figure 8



Figure 9

Consider now a much-speedier form of commercial transportation, the supersonic transport (fig. 9). The appeal of this type of aircraft to a sizable portion of the traveling public has been demonstrated by the Anglo-French Concorde. However, it suffers from several problems that resulted in this country not undertaking the development of such an aircraft: noise and fuel economy. Also, overall airplane economics are questionable. Nevertheless, Congress has deemed it important

for this country to continue research in the area of supersonic transports so that, should a decision ever be made to embark on its development, the technology will be there. Accordingly NASA has a continuing program directed at technology for supersonic transports which includes materials, structures, aerodynamics, and propulsion. Propulsion is obviously the key ingredient for such a high-thrust vehicle as a supersonic airplane.

The diverse requirements of a civilian SST, such as low noise, good efficiency at subsonic conditions, and outstanding efficiency at supersonic conditions, force the designer to consider a variety of alternative engine systems. An approach that is presently receiving much attention is the variable-cycle engine. The features of a variable-cycle engine are as follows: During takeoff, subsonic flight, and landing, the engine would operate like a turbofan, because the jet velocity would be low and hence the noise would be low. During supersonic flight, it would operate like a turbojet to give the very high jet velocities needed for efficient operation under supersonic conditions. Hence, there is interest in devices that are capable of changing their modes of operation to best suit the needs of each part of the flight.

NASA has major analytical and experimental programs underway with both Pratt & Whitney and General Electric to study various concepts for variable cycle engines. Breadboard engines are being used to examine some of the unique components and technologies required.

Figure 10 shows such an engine on the test stand. The features of this General Electric engine include internal valving, in order to shift the flow from one mode of operation to another, and multistream exit jets (at least two streams) with the velocities adjusted to minimize noise. (Incidentally, at the right of the picture may be seen a laser Doppler velocimeter (LDV) instrument which is used to measure the velocity in the jet plume emerging from the engine. This will be mentioned again later in the paper.)

The final commercial transport category to be discussed is commuters. This term refers to smaller aircraft that can carry 20 to 50 passengers. They are almost entirely turboprop aircraft, such as the one shown in figure 11. The current increased interest in commuter aircraft has been the result of the recent deregulation of the airline industry. This has permitted the certified trunk carriers to withdraw from their less profitable routes, often leaving little or no service to many smaller cities. In their place

COANNULAR NOISE TEST OF GE ENGINE

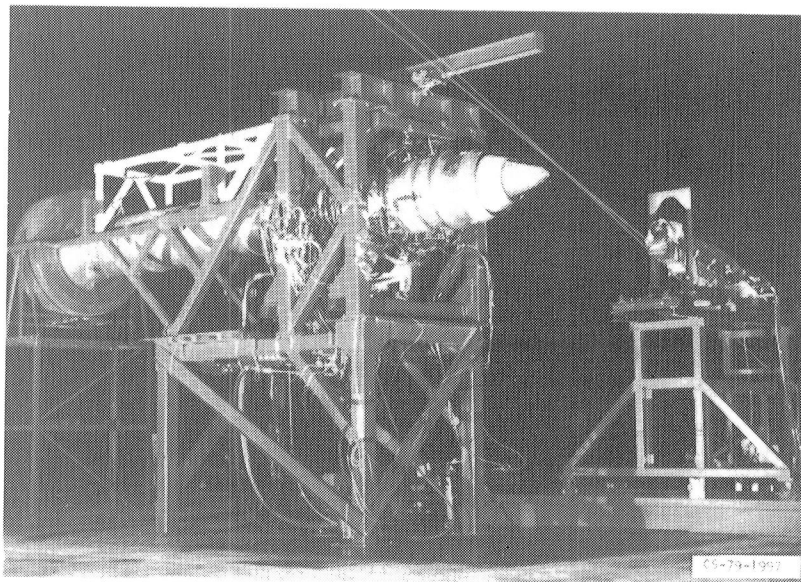


Figure 10



Figure 11

the commuter airlines have sprouted, offering frequent departures in smaller, more-economical aircraft. NASA is looking into what technologies might be useful to the newly important commuter aircraft industry. Of course that includes aerodynamics, structures, and the propulsion system. Figure 12 shows some of the unusual configurations that have been evolving from NASA-sponsored studies with industry. Noteworthy is a general tendency to put the propulsion system toward the rear of the aircraft so that the noise and vibration of the propellers would not be transmitted into the cabin. One concept uses pusher propellers; others use the standard forward configurations. Unusual wing arrangements and the use of canards are also being contemplated.

The technology needs for this kind of aircraft are still being studied. If appropriate, NASA will initiate a major program in the future.

General Aviation

The next part of this paper deals with the subject of general aviation, which is an extremely important part of the civil aviation sector. In fact, it is just about as important as commercials. There are many more aircraft on the general aviation scene, with about 85 percent of these being used for business. Despite the popular impression, recreational flying is only a small portion of the total. Thus, general aviation truly is an important part of our total transportation system.

General aviation is faced with problems similar to those of commercial aircraft:

- (1) Safety and reliability
- (2) Environment
 - (a) Community noise
 - (b) Cabin noise and vibration
- (3) Fuel
 - (a) Availability
 - (b) Consumption

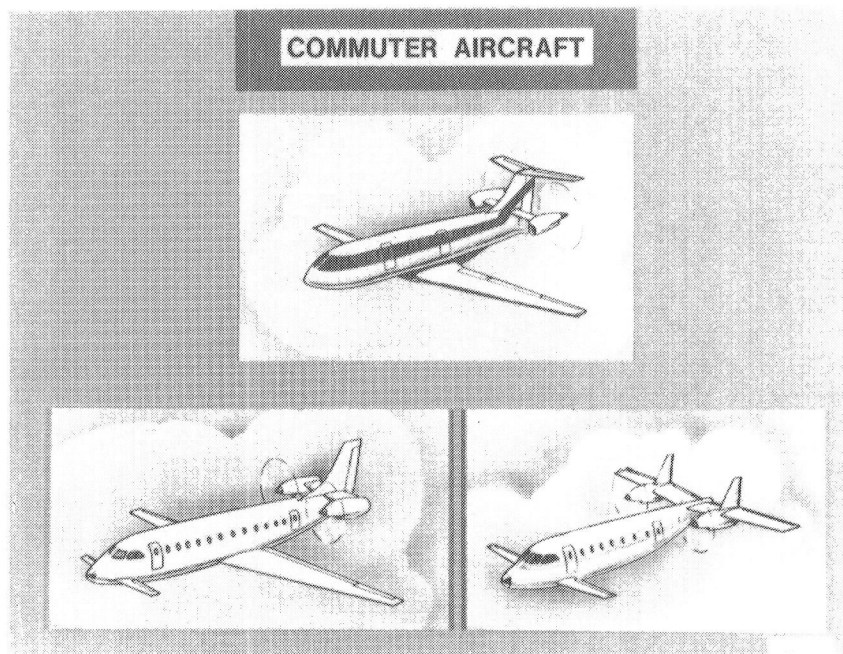


Figure 12

Safety and reliability head the list in recognition of the poorer record of general aviation as compared with the commercial transports. NASA is involved in several programs to try to improve that situation. The second and third items are repetitions of the same sort of problems affecting the commercial sector.

With regard to community noise, although these small airplanes tend to be relatively quiet, they also frequently operate from small airports in suburban or rural areas where the natural noise level is low and where this additional noise source is especially objectionable. In addition to the community noise, passengers and crew experience a lot of noise and vibration particularly in the smaller aircraft. (Any reader who has flown some of the small piston-engine aircraft is familiar with these defects.)

Shortages are of particular concern to general aviation because its image of being a frivolous energy consumer makes it susceptible to diversion of fuel to supposedly higher-priority users. Furthermore, it is heavily reliant on aviation gasoline, which represents such a limited market to oil refiners that they can be tempted to drop production during crises situations; this did occur recently.

There are many types of aircraft that fall within the broad category of general aviation. For the purposes of this paper they can be conveniently categorized by engine type (fig. 13). Many of these aircraft operate with intermittent combustion or IC engines (i.e., piston engines). Of the larger general aviation aircraft quite a few are turboprops. The fairly large number of high-speed, high-altitude aircraft known as executive jets are powered by turbojet or turbofan engines. NASA Lewis is looking at the needs of each of these engine systems.

Figure 14 shows one of the Lewis test cells with a piston engine installed. In general the experiments are directed toward achieving a better understanding of the fundamentals of combustion in these kinds of engine systems, and trying to determine techniques to reduce the fuel consumption as well as reducing emissions.

Additionally, alternative engines are being studied that might have an advantage over the current piston engines. For example, diesel engines are being looked at rather carefully (fig. 15). Current diesel engines are too heavy, but recent studies have shown that advanced technologies such as ceramic piston heads and substantial turbocharging can reduce the weight of these engines significantly. If the weight does come down, the superior fuel economy of a diesel cycle can be exploited.

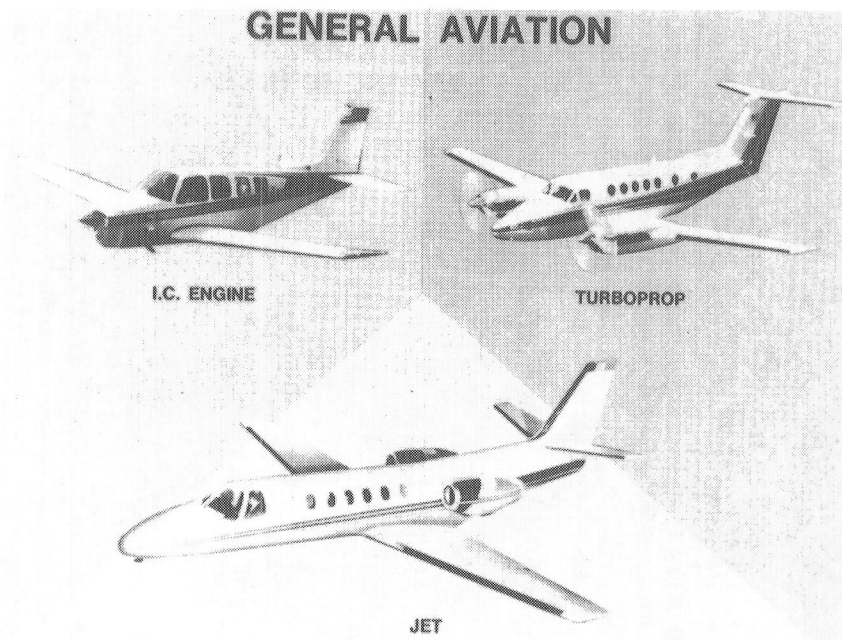


Figure 13

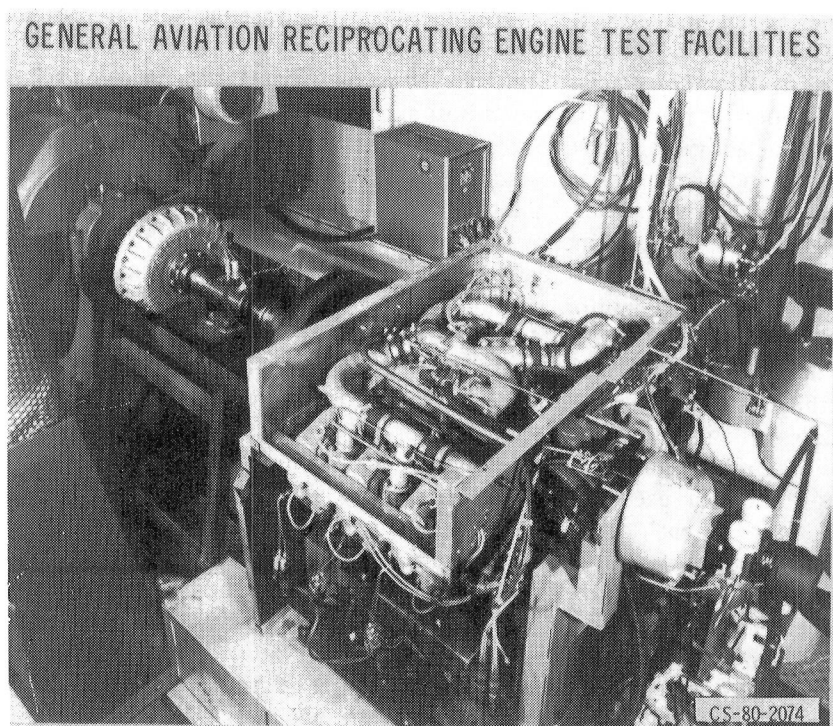


Figure 14

ALTERNATIVE ENGINES FOR GENERAL AVIATION AIRCRAFT

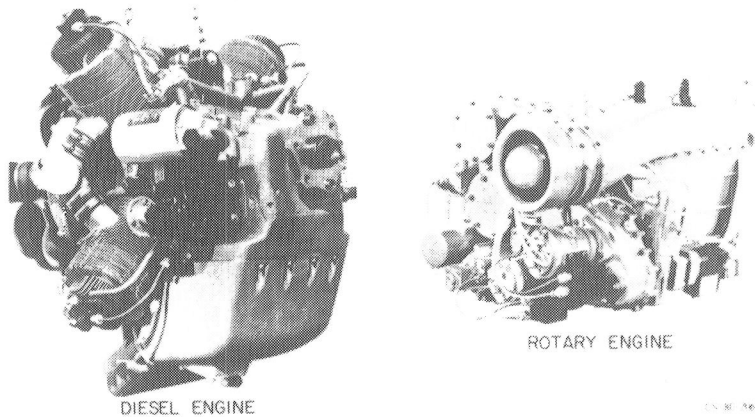


Figure 15

Another alternative concept is the rotary engine. It offers the potential of smooth operation, simplicity, and fairly low weight.

NASA is also continuing its studies of turbine engines, including an extension into the lower power range typical of pistons as well as improvement of the somewhat larger turbine engines that are currently used in the executive jets (fig. 16). A recently completed program called QCGAT (Quiet, Clean General Aviation Turbine) looked at the applicability of the technology of large transport engines to these smaller turbofan engines, particularly in relation to noise. There were two contracts put out, one with Garrett AirResearch and one with Avco-Lycoming. Preliminary studies were followed by the building and testing of experimental engines. Figure 17 shows one of these engines on a test stand at Lewis for evaluation. It has about 4000 pounds of thrust and could be used on an aircraft the size of a Lear jet for high-altitude, high-speed operation. It is dramatically quieter than the current engines being used.

NASA has an extensive program for the improvement of propeller systems for many applications. The high-speed efforts were described earlier. Additional work is aimed at general aviation



Figure 16

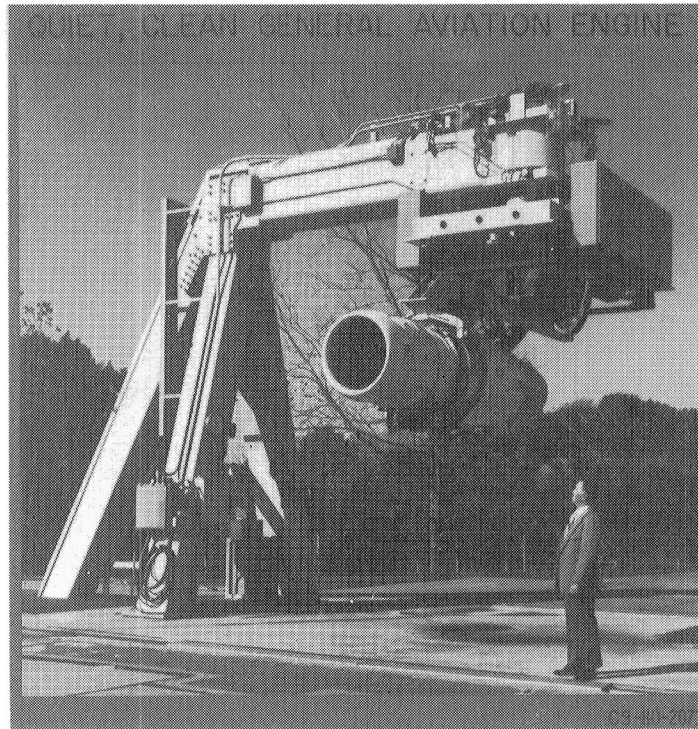


Figure 17

LOW SPEED PROPELLER WIND TUNNEL MODEL



Figure 18

propellers, such as the one pictured in figure 18. The goals of such technology involve reducing the cost of the propellers, improving their efficiency, which can be translated directly into fuel consumption, reducing the noise, and reducing the weight. As suggested in figure 19, advanced designs may utilize such techniques as swept blades or tip-mounted devices called winglets, which have been applied successfully to aircraft wings. (See, e.g., fig. 16.)

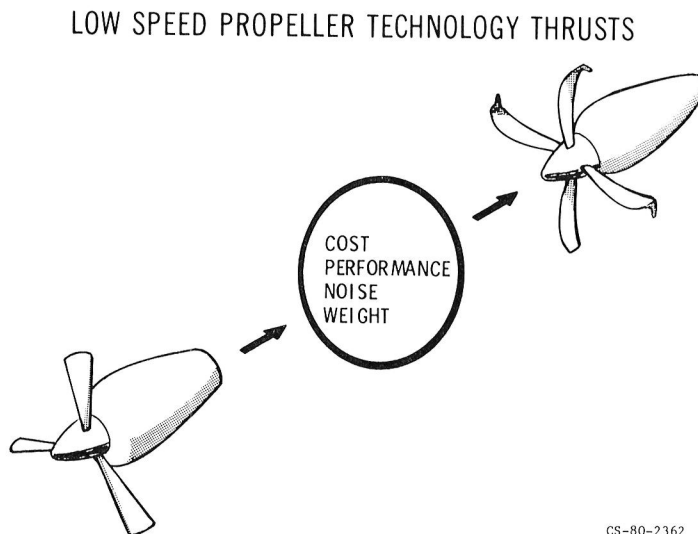


Figure 19

Emerging Technologies

The final part of this presentation treats the subject of emerging technologies. The point here is that several major technological advancements were made in the 1970's that are not directly related to, but that could have a large impact on, propulsion. Utilizing these in propulsion research in the 1980's could lead to major improvements across the board in the propulsion systems of the 1990's. Three general areas are

- (1) Advanced materials and processes
- (2) Computer revolution
- (3) Advanced electronics and optics

The major advances that have been emerging in the area of materials include such things as powder metallurgy (which opens the door to a whole, vast, new arena of alloys), single-crystal and directionally solidified turbine blades (which enhance the temperature level of turbine engines), and ceramics (which potentially offer lower cost as well as higher temperature capability).

Advances in computers have been so rapid and widely employed that the term "computer revolution" is often used. These high-speed, sophisticated "number-cruncher" machines enable the engineer to solve problems now in the areas of fluid mechanics or structures that were impossible just a few years ago.

And, finally, advanced electronics, microminiaturization, and the development of advanced optical techniques enable entirely new approaches to engine control. In some proposed engines it is necessary to control 10 variables at once. This is beyond the capability of the conventional controls, and advanced control systems are essential to these concepts.

In another application these electronic and optical improvements open the door to advanced instrumentation that allow the measurement of flow through such moving components as turbines and compressors, without having to insert physical probes that could disturb the flow by their presence. Several figures are offered to illustrate each of these emerging-technology categories:

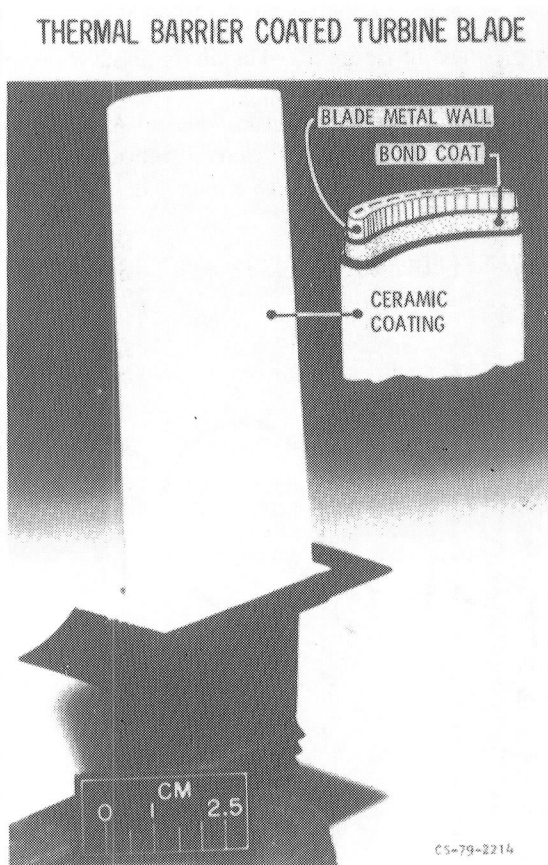


Figure 20

COMPUTER ANALYSIS AND GRAPHICS

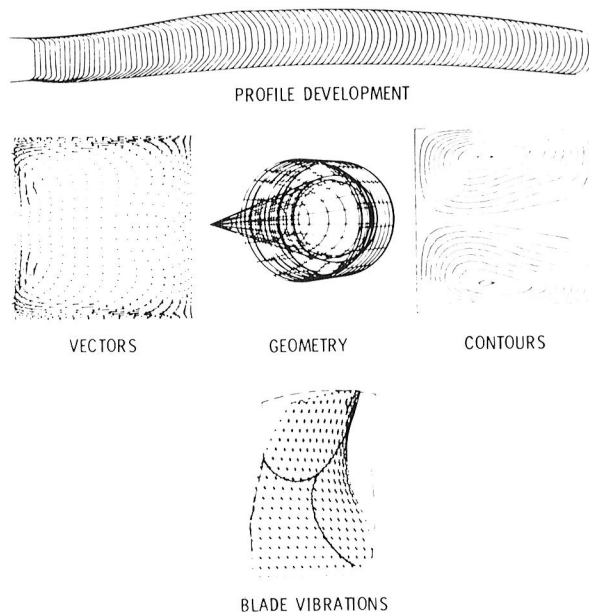


Figure 21

Figure 20 shows one application of ceramics. By placing a thin, insulating ceramic coating around a turbine blade, the combustion temperature of the cycle can be increased, which is very desirable, without any deleterious rise in the metal temperature of the blade. The key enabling technology is the bond coat between the base metal and the external ceramic. As the technology of bond coats evolves, ceramic coatings will be applied to all hot sections of engines.

Another example is in the computer area. As shown in figure 21 high speed computers allow visualization techniques that accurately predict the flow, including the boundary layer, through subsonic ducts. Vector analysis can yield pictures of cross flows within ducts. Contours of pressures and temperatures can be computed. The whole area of advanced structures and the prediction of vibrations and natural frequencies and so forth is just opening up using this new tool.

The third area mentioned was electronics and optics. Figure 22 is a picture of the previously mentioned LDV system being used here to measure the flow within a rotating cascade without having to put a probe inside. This nonobtrusive technique is considered a breakthrough in how one can measure what is going on within these complicated machines.

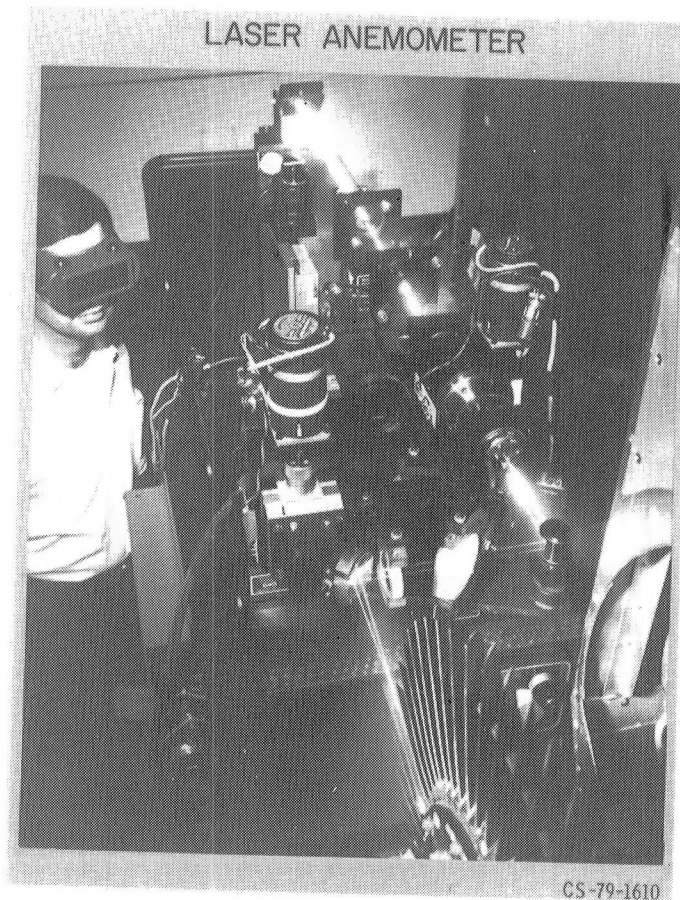


Figure 22

Final Remarks

The following list shows some of the many component and fundamental technologies that are being studied at Lewis to support aeronautical propulsion as well as the other areas:

Combustion and pollution	Structures
Heat transfer	Transmissions
Gas dynamics (ducts and rotating machinery)	Bearings, lubrication, seals
Controls	Materials
Acoustics	Computer sciences
	Instrumentation

To summarize, this paper has attempted to outline some of the opportunities and problems confronting the civil aviation sector. (Shortage of time did not allow coverage of the many interesting military vehicles, such as high-speed rotorcraft, all-weather rotorcraft (helicopters), VTOL aircraft, and a new series of high-performance aircraft for the Air Force.) Also discussed were some of the emerging technologies that will affect the propulsion systems of the future. It is hoped that this overview provides the nonaviation specialist a better picture of the many activities at Lewis that will contribute to improved air transportation in the years to come.

Large Wind Turbines—A Utility Option for the Generation of Electricity *

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National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

For the past several years the Federal Government has sponsored an expanding research and development program to make renewable energy sources for the generation of electricity a viable technological alternative to conventional generating capacity. One renewable energy source, wind energy, appears to be a particularly attractive candidate in the near term.

The Federal Wind Energy program, under the sponsorship of the Department of Energy (DOE), is directed toward the development of safe, reliable, cost-effective, and environmentally acceptable machines that will generate significant amounts of electricity. The largest element of the Federal program, large wind turbine development, is managed by the NASA Lewis Research Center. There are several ongoing wind system development projects oriented primarily toward utility application within this program element (ref. 1).

First-generation-technology large wind turbines (Mod-0A and Mod-1) have been designed and are in operation at selected utility sites. Second-generation machines (Mod-2) are scheduled to begin operation on utility sites in 1981. These second-generation machines are predicted to generate electricity at less than 4¢ per kilowatt hour (in 1977 dollars) when manufactured at modest production rates. However, to make a significant energy impact, costs of 2¢ to 3¢ per kilowatt hour (in 1977 dollars) must be achieved. When these cost goals are achieved, the major use of wind turbines by utilities will be as fuel savers. The Federal program will continue to fund the development, by industry, of wind turbines that can meet the cost goals of 2¢ to 3¢ per kilowatt hour.

Lower costs will be achieved by incorporating new technology and innovative system designs that reduce weight, increase reliability, and increase energy capture. The National challenge, however, is the acceptance by the utilities of wind turbines as part of their energy-generating capability and the creation of a competitive industry to produce wind turbines efficiently. The principals—Government, industry, and the utilities—are currently involved in meeting this challenge.

This paper provides an overview of the potential of wind energy in the United States, as well as an assessment of wind turbine operational experience, the current economic status, the environmental posture, and the status of the technology.

Wind Turbine Description

NASA now has six large wind turbines in operation, with four more scheduled to be placed in operation within the next year. Several of these wind turbines are pictured in figure 1. Of the total of 10 prototype wind turbines, five are Mod-0/Mod-0A machines, one is a Mod-1 machine, and four are Mod-2 machines. The Mod-0 and Mod-0A wind turbines have rotor diameters of 125 feet and rated electric power outputs of 100 and 200 kilowatts, respectively. The Mod-1 is a larger machine,

* Presented at American Power Conference, Chicago, Illinois, April 21-23, 1980.

WIND TURBINE TECHNOLOGY

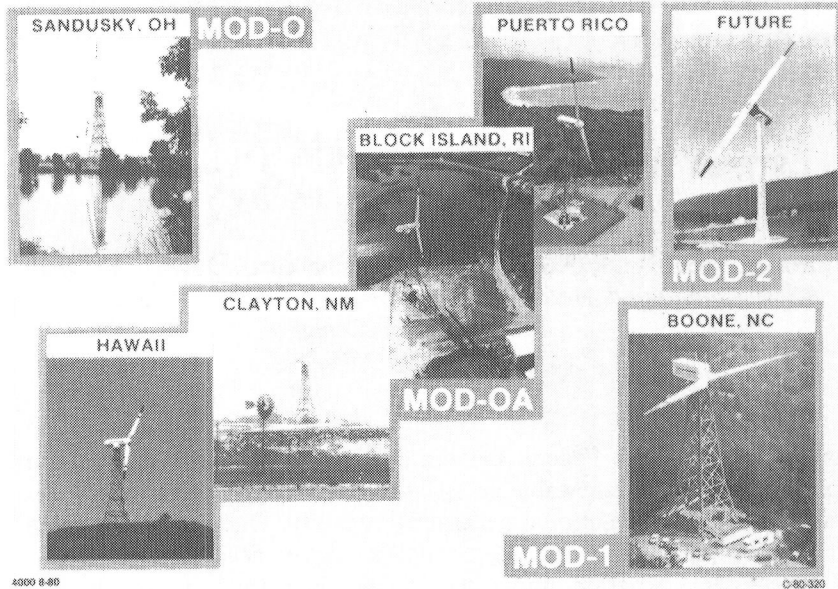


Figure 1

with a 200-foot rotor and 2000 kilowatts of rated power output. The Mod-2 will have a 300-foot rotor and 2500 kilowatts of rated power output. The rotor and the machinery pod (or nacelle) containing the drive train and other equipment are mounted on a tower 100 feet high for the Mod-0A's, and 200 feet high for the Mod-2. The Mod-0, Mod-0A, and Mod-1 wind turbines are first-generation machines that rely on high natural frequencies ("stiff" design) in the tower and rotor to avoid rotational frequency resonance. As shown in figure 2, these first-generation machines are typified by the truss tower and rigid rotor (no hinge motion between the rotor and the main shaft). In contrast the Mod-2 is a second-generation "soft" design. The lower frequency tube tower and the teeter-hinged rotor contribute to the marked difference in the appearance of the Mod-2 from the earlier designs.

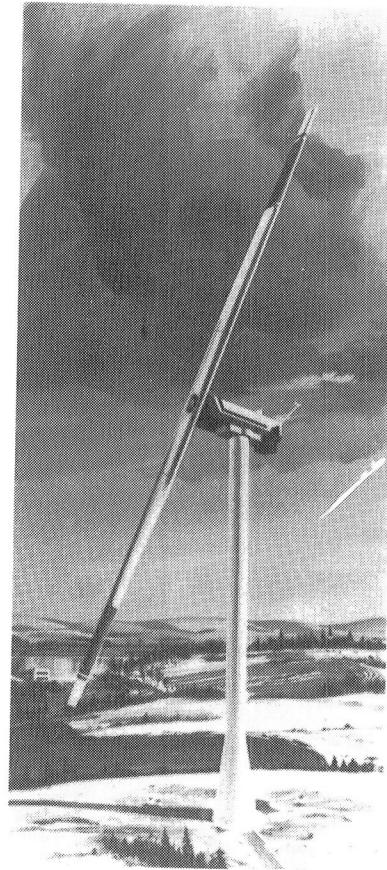
The axis of rotation of the rotor is parallel (or horizontal) to the ground—thus the name horizontal-axis wind turbine. The propeller-like rotors have two blades and operate at low rotational speeds of about 20 to 40 rpm. A sketch of the interior of a 200-kilowatt wind turbine nacelle is shown in figure 3. The gearbox increases the rotor rotational speed to drive a standard synchronous generator at its design rpm. The generator output is connected to a utility network. There are two orientation control systems. The yaw control, consisting of an electric motor, a pinion shaft, and a bull gear, orients the nacelle in the direction of the wind. The pitch control system feathers the blades to control power, to start up, and to shut down. The pitch control is similar to that of an aircraft propeller.

All the wind turbines in operation or under development are automatically (microprocessor) controlled. Their operating map is shown in figure 4. The units start when the wind speed reaches about 10 mph (at a 30-ft height). As the wind speed increases, the power output also increases until rated power is attained. The power is then held constant (by feathering the blades) at the rated value until the cutout wind speed of approximately 35 mph (at 30 ft) is reached. At wind speeds exceeding this cutout speed, the wind turbine is shut down. It will not usually be cost effective to design the machines for operation at higher wind speeds. The annual energy content of the wind is small at high speeds because the wind does not reach these wind speeds often enough at most locations.

TECHNOLOGY ADVANCEMENT



FIRST GENERATION
(MOD-0A AND MOD-1)



SECOND GENERATION
(MOD-2)

Figure 2

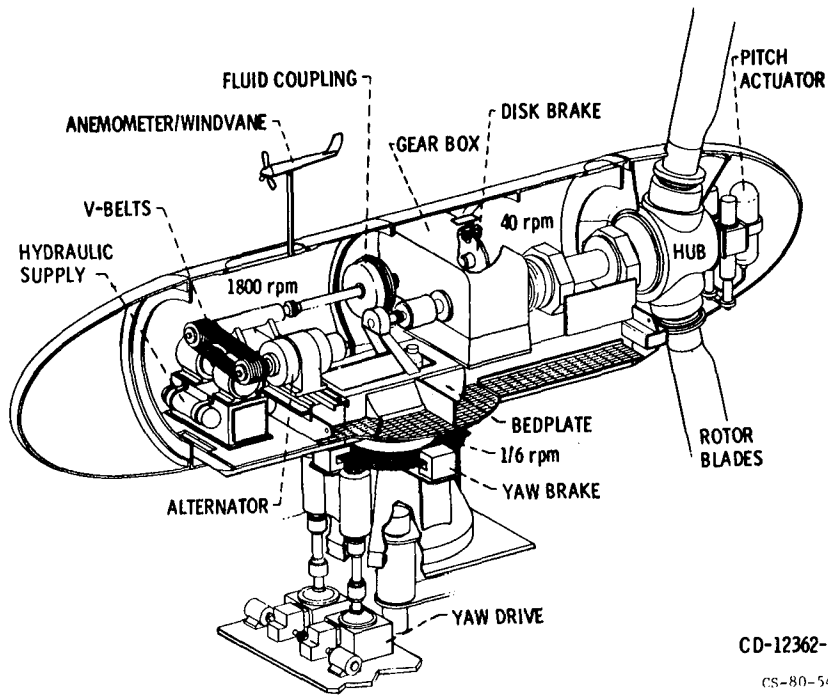
Assessment of Wind Energy Potential

The general land areas in the continental United States with high wind energy potential are shown in figure 5. These areas were identified in the investigations performed in reference 2. In general the Rocky Mountains block the prevailing west-to-east flow of air and the high wind potential areas are thus either through the great pass regions or around the southern end of the Rockies. Thus Wyoming and the Texas Panhandle have large areas of excellent wind potential. Other good areas are in the pass regions of Oregon, Washington, and California and in the Northeast as a result of off-shore air mass movement. A land-use survey was also conducted in reference 2. The results of that survey are summarized in figure 6, which shows the land available for wind turbines categorized into moderate, good, and excellent. Such land totals some 1.5 million square miles, with some 470 000 square miles shown as good or excellent. Included are mountain ridges and tops, rivers, tall-tree forests, and urban areas, which are not suitable for wind turbines. When such areas are removed, a total usable area of 214 000 square miles exists in the moderate-to-excellent category.

Aerodynamic interference of one turbine on others downwind is minimized when such turbines are spaced at least 15 diameters apart. Experiments now under way (the Mod-2 wind turbines will be

MOD-0A 200 kW WIND TURBINE

SCHEMATIC OF NACELLE INTERIOR



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CS-80-541

Figure 3

WIND TURBINE OPERATING RANGE

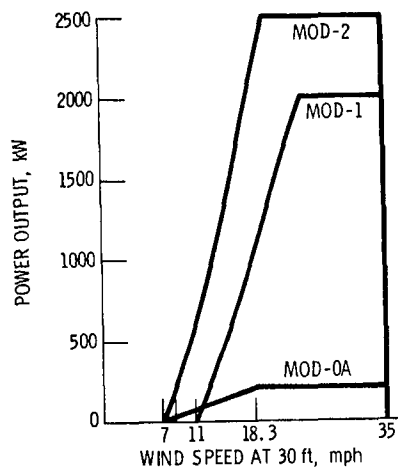


Figure 4

WIND ENERGY IN UNITED STATES

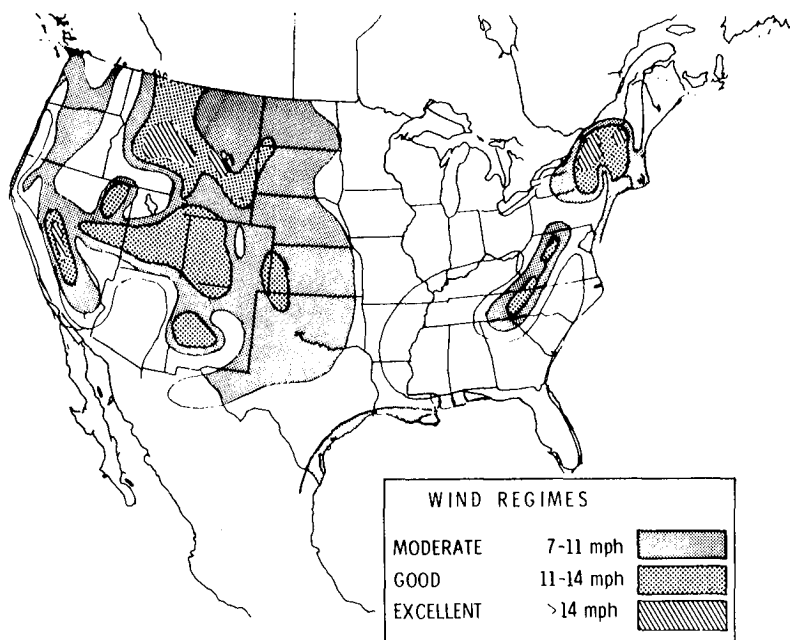


Figure 5

LAND AVAILABLE FOR WIND TURBINES

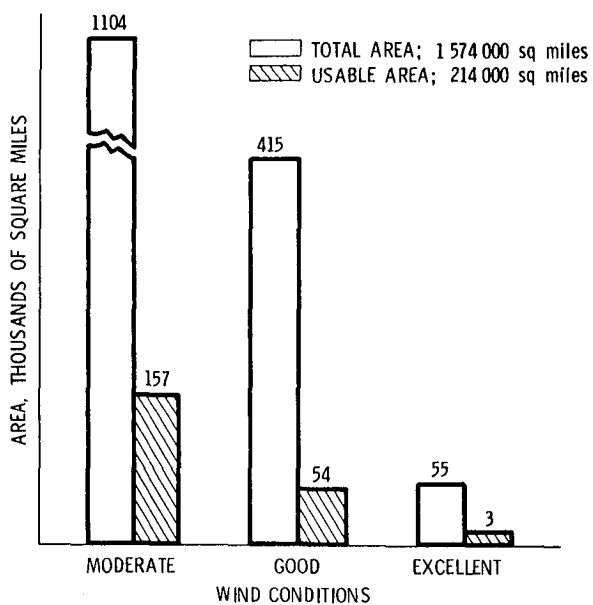


Figure 6

grouped with separations of 5, 7 and 10 diameters at Goldendale, Washington) may show that this spacing can be reduced to 10 diameters or less, especially in regions that have strong prevailing wind directions. If 10-diameter spacings are practical, the number of Mod-2's that can be installed is 2 1/4 times that which could be installed at a 15-diameter spacing. On the conservative basis of a spacing of 15 diameters, the number of Mod-2 wind turbines (300-ft diameter) that could be installed in each type of usable land area is shown in table I. This table shows that enough land area exists for 340 000 large Mod-2 wind turbines. (A Mod-2 wind turbine requires about 1 acre of ground after installation (4 acres during installation).) Thus, only 500 square miles of land out of the 214 000 square miles of wind turbine territory are actually required for the operational turbines (access roads and right of ways not included). Table I shows that the 340 000 Mod-2 wind turbines will produce on the order of 4.9 quads of electricity annually (where 1 quad = 300 billion kWh of electricity, or 172 million barrels of oil). Considering the powerplant efficiency of oil-fired utility systems, such generation will save 14.7 quads of energy per year, equivalent to some 2.5 billion barrels of oil.

TABLE I.—MAXIMUM WIND RESOURCE POTENTIAL

	Usable area, sq mi	Number of Mod-2's	Electricity produced per year, quads ^a	Energy saved per year, quads ^a
Moderate	157 000	250 000	2.7	8.1
Good	54 000	86 000	2.0	6.0
Excellent	3 000	4 800	.2	.6
Total	214 000	340 000	4.9	14.7

^a 1 Quad = 10¹⁵ Btu (300 billion kWh of electricity)
= 172 million bbl oil.

Many of the moderate wind sites will be marginal producers of cost-effective electricity, but even if they are eliminated, there is still the potential of 6 to 7 quads saved per year. This places wind energy generation in an attractive position as a potential producer of a large amount of energy. This is more fully dramatized by noting that in 1977 (fig. 7) gas and oil electric generators consumed 7.4 quads—an amount just about equal to the amount of fuel that can be saved by wind turbine generators if only the usable areas with good and excellent winds are employed. In summary, the wind energy resource has great potential. Deployment of approximately 90 000 Mod-2 size wind turbines at good and excellent wind sites can result in the large savings of 6 to 7 quads of fuel.

Wind Turbine Economics

The cost of electricity (COE) for a wind turbine is a measure of the value of the system and is reported by Ramler and Donovan in reference 3. The cost of electricity for wind turbines employed in a utility electrical network is computed as follows:

$$\text{COE, ¢/kWh} = \frac{(\text{Capital costs, \$})(\text{Fixed charge rate, \%})}{\text{Annual energy, kWh}} + \frac{(\text{Annual O\&M Costs, \$})(\text{Levelized factor})(\times 100)}{\text{Annual energy, kWh}}$$

ENERGY USE IN U.S. IN 1977

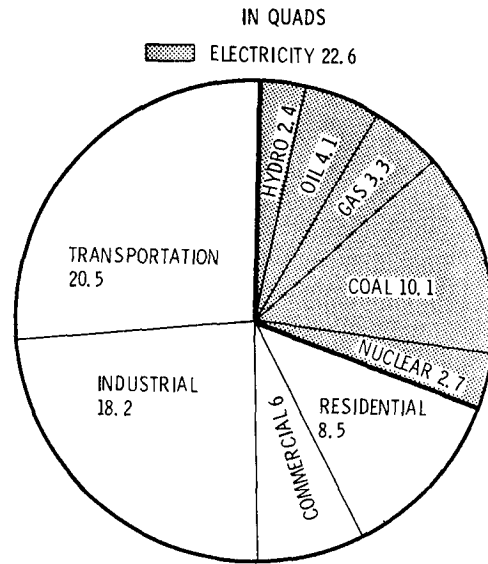


Figure 7

In most applications for the near future wind turbines will be used as fuel savers. The electric energy produced by a wind turbine in a utility system will enable the utility to reduce or shut down the generation from conventional, fuel-burning powerplants that would otherwise be required. The fuel thus saved can be credited to the wind turbine. In this mode wind turbine power would be used whenever it is generated.

The ability of wind turbines to save fuel will, in part, depend on how readily a utility's conventional powerplants can respond to changes in the wind power being produced. For modest amounts of wind power the wind power variations are expected to be of the same order as normal load variations and will appear to be a negative load to the rest of the system. At some level of wind power contribution (perhaps greater than 10 percent of system peak load), the wind variability may adversely affect system stability in the absence of short-term storage. This level must be determined by each individual utility because it depends on the conventional mix, the characteristics of the load, the variability of the wind at the wind turbine site, etc.

Most utilities use economic dispatch. Units with the lowest operational cost are dispatched first and those with the highest operational cost are dispatched last. With this strategy wind turbines will tend to save the most costly fuel being burned at any particular instant of time. At times the fuel saved will be relatively expensive gas turbine fuel (oil or gas), but at other times it will be relatively inexpensive baseload coal. (It is assumed that nuclear plants will not be throttled to save nuclear fuel.) Thus the first increment of wind turbine power added by a utility will be the most attractive. As more wind turbines are added to a system, they will tend to save less costly fuel as they meet more of the system load. Here again, each utility's fuel saving per kilowatt hour of wind turbine energy produced will be different depending on its generation mix, its cost of fuels, etc. Ultimately fuel savings attributable to wind turbines must be determined on an individual utility basis. The Department of Energy has supported a number of studies aimed at developing generic analytical techniques and approaches that can be used by utilities in this determination.

To obtain some overall feel for the COE requirements of wind turbines, one can examine the price of fuels paid by utilities. As noted, the first increment of wind turbine power added by a utility will tend to save the most expensive fuel being used at any instant of time when the wind turbine produces power. Successive additions will save fuels that are decreasingly costly. Thus for modest amounts of wind turbine power the average price of fossil fuels paid by a utility affords a conservative measure of

the COE that wind turbines must achieve to be generally attractive to a utility. This is a conservative approach in that the average price of fossil fuels for most utilities will be heavily weighted to their baseload fuel prices because of the predominance of baseload generation.

The estimated average price range for fossil fuels paid by 310 utilities in 1977 is shown in figure 8. The utilities included represent nearly 98 percent of all U.S. power generation by fossil fuels. Also shown is a projected cost range for 1977 to 2007 based on fuel costs escalating at the same rate as the inflation rate. Recent experience with fuel escalation has shown this to be a conservative assumption. For wind turbines to be an attractive investment as fuel savers, the projected COE must compare favorably with this projected fuel cost range. If the COE of a wind turbine is below about 6¢ per kilowatt hour, some utilities will become interested. On the other hand, if a wind turbine's projected COE is near 2¢ per kilowatt hour nearly all utilities would become interested. Therefore the wind energy cost goal of 2¢ to 4¢ per kilowatt hour (in 1977 dollars) shown on the chart is considered to be the range that will result in a substantial wind turbine market.

The position of DOE/NASA-sponsored large wind turbine systems in the utility market is summarized in figure 9. The first-generation system (Mod-1) is not competitive. However, the second-generation system (Mod-2) will produce electricity at less than 4¢ per kilowatt hour (in 1977 dollars) and therefore will penetrate the "substantial market" range. The third-generation system (Mod-5) will penetrate the market even further, with a projected COE of less than 3¢ per kilowatt hour (in 1977 dollars).

Environmental Considerations

Among the attractions of wind turbine system technologies is the fact that they are for the most part environmentally benign. They certainly can be expected to have relatively little effect on air and water quality, on ecological systems, or on solid-waste disposal requirements. Nevertheless, it has

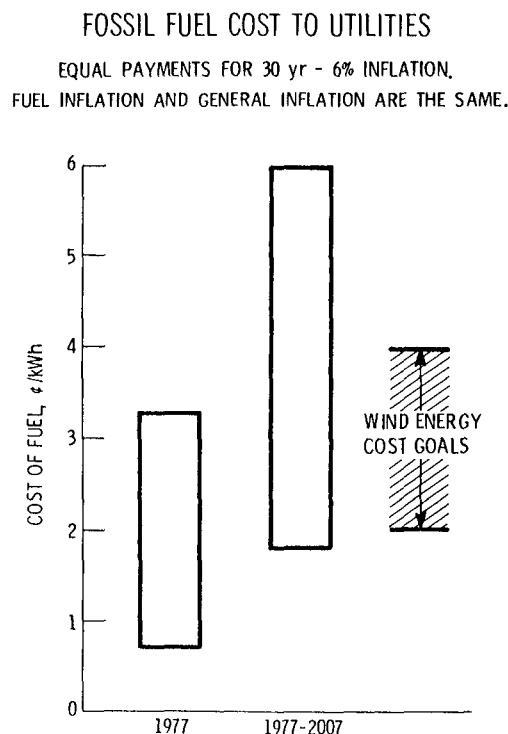


Figure 8

COST TRENDS OF LARGE WIND SYSTEMS

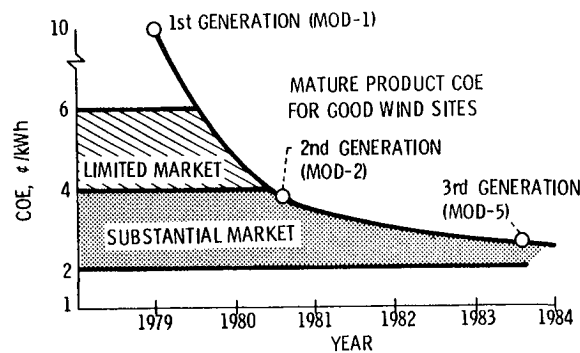


Figure 9

been important during the developmental stages to examine all possible environmental ramifications. Although a few aspects of environmental impact result in important siting considerations, no serious issues have been identified that would impede the development of wind turbine systems technologies.

All large wind turbine systems developed by DOE and NASA are designed with safety of the environment as a primary consideration (ref. 4). Foremost in this consideration is the safety of the public and of the construction and maintenance personnel. An example of such considerations is the development of an ice detection system that automatically shuts down a wind turbine generator during icing conditions to avoid the hazards to personnel and property of ice being thrown from the blades.

Three effects on the environment have been identified as possibly important considerations in the siting of wind turbine generators. The first of these, television interference, has been found to occur if large wind turbine generators are placed in areas where antenna reception is predominant. A definite zone of interference is being defined in order to identify acceptable sites (ref. 5). Tests are under way on types of television antennas that will not be affected by wind turbine operation. Obviously, homes supplied by cable television are not affected by the wind turbine. Another environmental impact important to siting is the noise associated with the motion of the blades (ref. 6). This noise, although modest in most cases, can have an adverse effect on the public. For example the Mod-1 experience at Boone, North Carolina, has shown that intermittent pressure waves (very low-frequency noise) have caused disturbing sounds in homes located close to the turbine. This is an annoyance, and NASA is conducting investigations to determine the cause and to arrive at a proper solution. The third possible environmental effect is land use and the associated potential visual pollution that may become an issue when large numbers of machines are deployed in an area. As a result, aesthetics and limited land intrusion are considerations in the wind turbine design efforts.

Early Operational Experience

At present the greater portion of wind turbine operational experience is being produced by the four operational Mod-0A machines located at Clayton, New Mexico; Culebra, Puerto Rico; Block Island, Rhode Island; and Oahu, Hawaii. The majority of operating experience and data to date has come from the Clayton machine. This machine's operation is reported in reference 7. The chronology as of July 1980 is as follows:

First rotation.....	November 1977
Utility turnover	March 1978
Operating time, hr	7300
Energy output, kWh	650
Average percentage of Clayton power, percent	2 1/2

The system design and utility-wind turbine compatibility have been validated. Component problems in blades, controls, and electronics were identified early in the operations. However, the annual energy output has been below predictions because of losses in the start-stop cycle and yaw error.

The Clayton, New Mexico, site was an excellent choice for the first utility-operated wind turbine. The machine has been well received by the residents of the community, and its proximity to the municipal powerplant has made it convenient for service personnel when on-site presence is required. The size of the utility is such that the wind turbine can make a small but measurable contribution to the power output of the municipal system. During the period of its operation the wind turbine has produced 2 1/2 percent of the total energy used by the community and has, on occasion, during early morning hours produced over 20 percent of the total power requirements of the community. This machine has proven to be a good neighbor with low noise characteristics.

Major system design components that have been validated are the mechanical system, the control system (pitch, yaw, and microprocessor), the safety system, and the remote control and monitoring system. Compatibility with the Clayton diesel generator system has been demonstrated and is reported by Reddoch and Klein (ref. 8). The Clayton system frequency has a characteristic natural mode of oscillation of 3 hertz and a predominant mode of 1.33 hertz. The 1.33 hertz is due to the blades' rotational speed, the wind shear, and the tower shadow. There was some concern that the wind turbine might excite the utility system frequency, but it clearly does not. The operation of the wind turbine with the utility has been very satisfactory. This is partly due to the high per-unit resistance of the distribution line connecting the wind turbine to the central station. This line appears to attenuate any wind turbine oscillations to the point that they are not sensed by the diesel generators. In summary, there has been no problem in maintaining synchronism. Operation and routine maintenance have been handled by the Clayton utility operations personnel.

The major component problems that were identified early in the program were blade fatigue, control system mechanical and electronic component failures, and drive system components such as generator bearings.

Blade problems have arisen as a result of early design deficiencies and higher-than-expected loads. The blade design in the area of the root did not provide adequate strength at the joint between the wing-like structure and the steel root shank. Stress concentrations and wear in this area caused fatigue cracks after only 1000 hours of service. Also, blade loads higher than predicted were encountered in service at Clayton. These high loads occurred (1) at wind speeds near the cutout wind speed of 17.9 meters per second during the safety system shutdowns, where a high feather rate is used to stop the rotor, and (2) in some periods when the yaw brake did not supply normal restraint during yaw corrections.

Adjustments have been made to eliminate these problems in the future. The blade root area has been redesigned to provide the additional strength and better load paths for load transfer to the root fittings; a blade load monitor has been added to the safety system that will shut the machine down if high loads are encountered; and the high feather rate used in safety system shutdowns was reduced.

The control system has encountered the usual control system hardware and software problems and logic changes that are associated with early operation of any new system. No fundamental problems have been observed. Typical of the character of the issues, the Clayton wind turbine experienced electrical noise and heat buildup in the microprocessor and a number of false safety system shutdowns before proper adjustments and settings were determined.

A summary of the Clayton machine performance is shown in table II. Over the past year the wind turbine has produced 57 percent of the energy expected. The reduced energy production was primarily caused by mechanical and electrical problems that decreased the expected operating time. However, in recent months, as typified by August 1979 (table II), the power production has dramatically increased and is approaching the expected energy production. The reduced annual energy production in August 1979 was caused primarily by three factors: excessive start-stop time, yaw error, and a low power setpoint. Design modifications were then made to correct the blade structural and electronic problems. The start-stop time was also decreased by 50 percent, the yaw

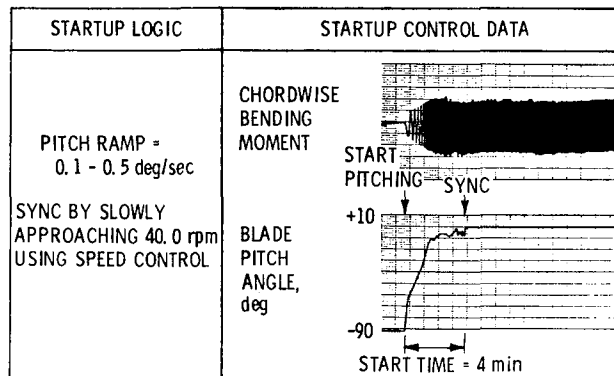
TABLE II.—PERFORMANCE OF MOD-0A (200 kW) CLAYTON WIND TURBINE

Time	Predicted	Actual	Synchronous time wind available	Comments
	Energy output, kWh			
August 1978 to October 1979	500 800	292 000	0.57	Energy output below expected (0.9) because of structural and electronic problems
August 1979	38 500	31 170	.83	Energy output only slightly below predicted because of start-stop time, yaw error, and low power setpoint

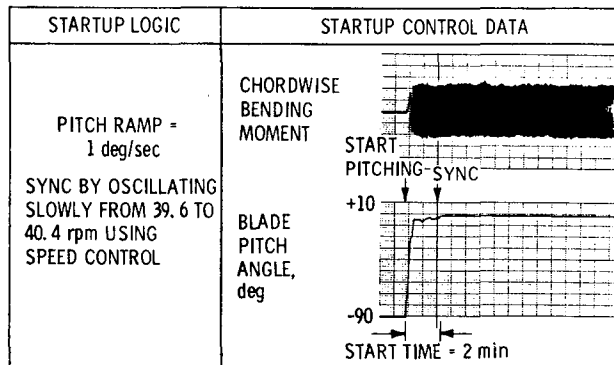
error deadband was decreased from ± 25 degrees to ± 7 degrees, and the power setpoint was adjusted to produce 200 kilowatts.

The original startup control system varied the blade pitch during the starting sequence at a rate from 0.1 to 0.5 degree per second and then approached synchronism by varying the pitch rate such that rpm slowly approached the synchronization rpm of 40. This procedure consumed an average of 4 minutes, as shown in figure 10(a). A new control sequence wherein the blade pitch rate during starting is increased to 1 degree per second and synchronized by slowly oscillating the blade pitch near 40 rpm reduced the startup time to 2 minutes, as shown in figure 10(b).

MOD-0A STARTUP



(a) ORIGINAL STARTUP CONTROL SYSTEM.



(b) IMPROVED STARTUP.

Figure 10

IMPROVED YAW ERROR CONTROL MOD-0A WIND TURBINES

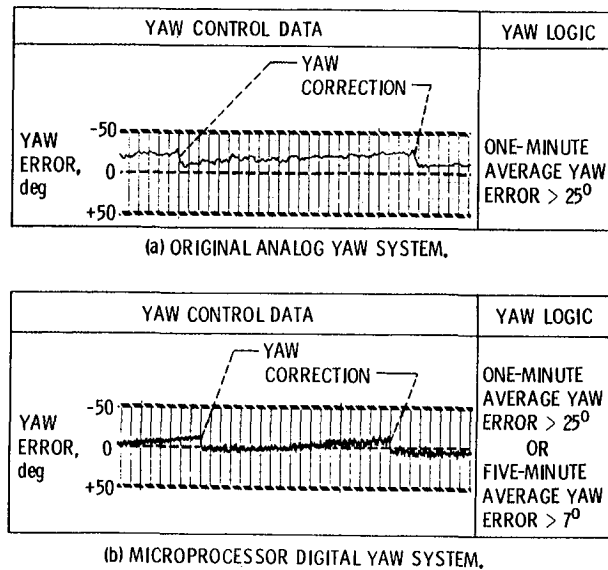


Figure 11

The original yaw control system was set up such that the wind direction could be misaligned up to 25° with no correction being initiated by the yaw control system. This allowed long periods during which considerable energy was lost, as shown by the trace in figure 11(a). A recent modification to the yaw system was made whereby if the wind error is more than an average of 7° for more than 5 minutes, a yaw correction is initiated. This system has given good results and holds the yaw error and thus energy losses due to yaw error to a minimum, as shown by the trace in figure 11(b).

The 1/2-hour averages of power output variation with wind speed for the Clayton machine are shown in figure 12. The general trend of measured power output agreed with the predicted output except for wind speeds near the rated wind speed. As a result of such measurements, it was concluded that the rated power setpoint of the power control system was set at 180 kilowatts rather than the current value of 200 kilowatts. Adjustments have been made, and the preliminary results show that correcting the power setpoint has solved this problem.

Preliminary results have indicated that these three control system improvements have increased the energy output.

The DOE/NASA Mod-1 wind turbine generator installed on Howard's Knob near Boone, North Carolina, was dedicated on July 11, 1979. With a rated power of 2 megawatts and a rotor diameter of 200 feet, the Mod-1 is the largest wind turbine ever constructed. Initial operation has produced preliminary test data on output power versus wind speed, rotor blade loads, system dynamic behavior, and start-stop characteristics. Figure 13 shows the power output versus wind speed measured at the present time and as of October 1979 (ref. 9). Although this is very early in the operation of this large machine, the data do show that the Mod-1 is generating the power that was expected.

A key element of the Mod-1 program that is being watched with interest is rotor blade structural performance. The largest Mod-1 blade loads, both by calculation and observation, occur during rapid feathering of the blades and stopping of the rotor from its overspeed limit of 38 revolutions per minute. Figure 14 shows a comparison between design loads for this condition and measured loads at three stations along the blades. The measured loads are the maximums of flatwise bending moments measured with strain gages while the blades were being feathered at a variety of rates. In the inboard

POWER VS WIND SPEED FOR MOD-0A WIND TURBINE
DATA FOR AUG. 1979

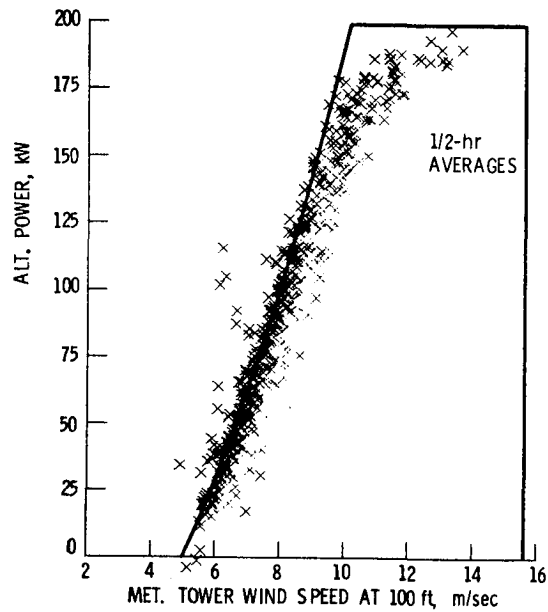


Figure 12

MEASURED AND DESIGN POWER OUTPUT FOR MOD-1 WIND TURBINE

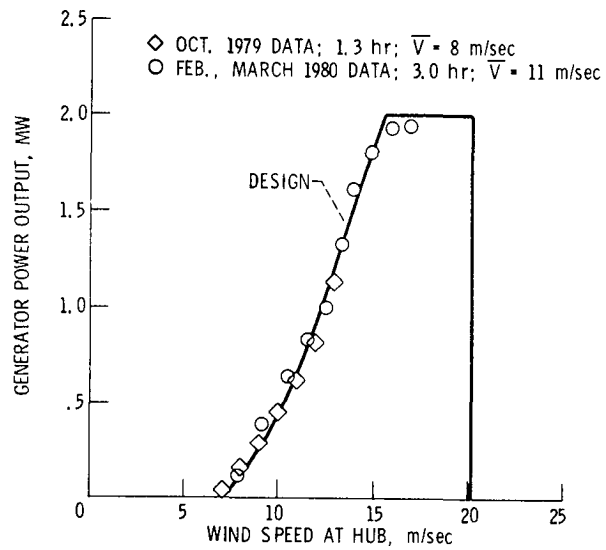


Figure 13

MEASURED AND DESIGN FLATWISE BENDING LOADS FOR MOD-1 WIND TURBINE

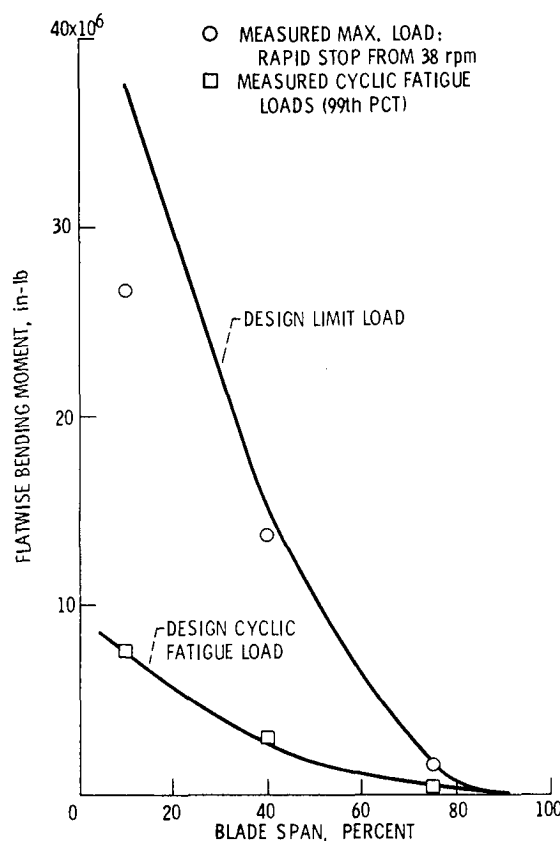


Figure 14

half of the blade the largest measured loads are less than the design limit loads. In the outboard regions of the blade, however, measured loads appear to equal predicted limit loads. In general, the procedures for establishing limit loads have been verified by these test data.

The fatigue design procedures used in the Mod-1 project can be assessed by using the summary of the blade flatwise cyclic fatigue bending moments accumulated to date shown in figure 14. The moments cover all wind speeds and directions in the operating range, starting and stopping transients, gustiness conditions, etc. The measured fatigue load spectrum agrees well with the design spectrum. Thus there is sufficient evidence to predict both design limit and cyclic loads on wind turbine blades with confidence.

In the early operation of the Mod-1 machine, control system hardware and software problems (similar to those with the Mod-0A) were also encountered. Minor software and hardware modifications have been made to correct the deficiencies, and the control system is now performing satisfactorily. Comprehensive investigations of noise and television interference are currently under way.

In summary, our early operational experience with these machines indicates that the design approach is correct, and the wind turbine/utility interface has presented no major problems. Additional operational experience is, however, required to evaluate long-term reliability, but no technological "breakthrough" is needed to make wind energy a viable energy alternative to other more conventional forms of energy.

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Progress in Materials and Structures at Lewis Research Center

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The Lewis Research Center is NASA's focal point for the development of power and propulsion system technology. Aircraft gas turbine engines and rocket engines have traditionally received major attention. Because of this background, the Department of Energy has asked Lewis to assume an active role in the development of automotive gas turbine and Stirling engines as well as the technology for advanced electrical generation at both central utility stations and industrial cogeneration locations.

The development of successful power and propulsion systems requires the integration of many factors related to both improved materials and to design methodology. These systems require materials of high strength and high temperature capability which at the same time are lightweight, easily fabricated, and low cost. Moreover, for most applications those requirements must be met without sacrificing component or system life. To ensure the long lives, Lewis researchers are involved in the areas of design, life prediction, and nondestructive evaluation.

The intent of this paper is to familiarize northeastern Ohio business people with selected areas of our materials research, to indicate where the materials and design technologies now stand, to highlight some of our contributions, and to indicate areas under continued investigation.

High Temperature Materials

Figure 1 schematically shows an aircraft gas turbine engine in cross section. Incoming air (left hand side of the figure) is highly compressed and then directed to the combustor where jet fuel is added.

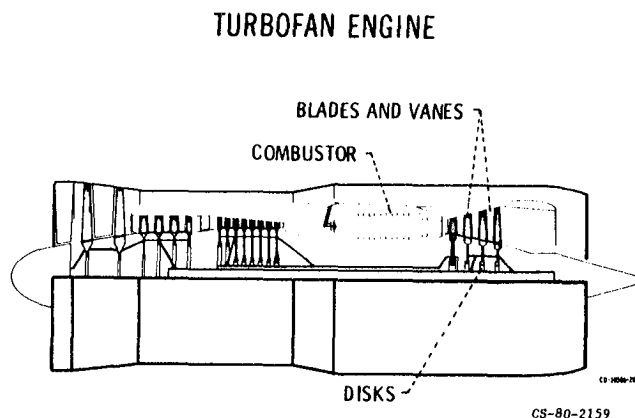


Figure 1

Flame temperatures can exceed 1500°C ($\sim 2750^{\circ}\text{F}$). Vanes operating at high temperature but low stress direct the hot gases against the turbine blades. The blades, in extracting power from the hot gas stream, experience the worst combination of temperature, stress, and corrosive attack in the engine. The rapidly rotating disks that hold the blades run at even higher stresses but at more moderate temperatures.

To manufacture turbine disks that will carry the high mechanical loads imposed by the rotating blades, we are developing advanced powder metallurgy techniques. One such concept involves the development of dual property disks. This approach involves a hollow metal container or can having the approximate shape of the final disk. The can is rotated and partially filled with powders of one alloy. The process is continued by completing the filling operation with powders of a second alloy. After sealing the can the powder is compacted to full density by the combined effects of temperature and pressure in a hot isostatic press. After inspection the disk is machined to final dimensions. The resultant disk consists of two alloys: one chosen for creep resistance located at the disk's rim, and the other chosen for low cycle fatigue resistance located throughout the remainder of the disk and at the bore. In this way the properties of the disk can be tailored through controlled powder compositions, resulting in improved performance. Additional benefits of the use of the powder metallurgy process are increased homogeneity of the resultant materials leading to smaller potential defects and thus longer potential lives. Materials costs are significantly decreased because the final pressed compact is close to the actual disk shape and thus requires little supplementary machining.

To improve the performance of turbine blades, which are exposed to high stress, high temperature gradients, and a corrosive environment, we are casting metal into a specially designed mold which extracts the heat only through the bottom (fig. 2). In this way solidification starts at the chill and proceeds through a tortuous path which allows only a single grain to grow. The product is a single-crystal turbine blade (ref. 1). Because grain boundaries are absent, material made this way has superior resistance to cracking caused by thermal cycling. Together with compositional changes permissible in single crystal castings, the superior thermal fatigue resistance allows the blade to be used at temperatures approximately 75°C (150°F) higher than a conventionally cast counterpart.

Turbine vanes are directly exposed to the high temperature gases leaving the combustor and thus must have high melting temperatures as well as moderate strength at high temperature. To extend the

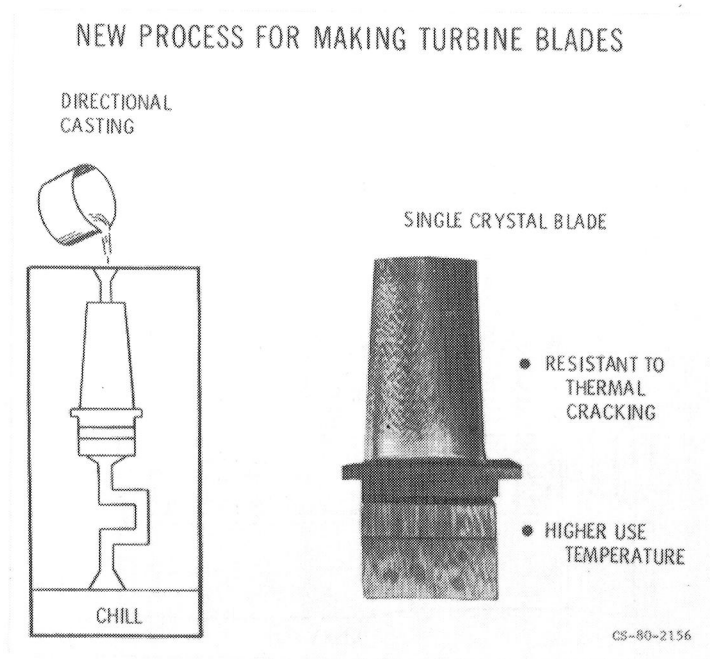


Figure 2

useful operating temperature of turbine vanes, Lewis has participated in the development of materials that are strengthened at high temperatures by the presence of very fine dispersed oxide particles (ref. 2). The first step in manufacturing an oxide dispersion-strengthened material is to mix (knead) fine oxide particles into metal alloy particles (fig. 3). To do this we use the product of one northern Ohio business, the attrition mill, which is a high-energy, rapid, stirred ball mill. (We are also using such mills to reduce the size of ceramic particles for our ceramic materials development activities.) Once milled, the powders are sealed in a metal container and extruded through a die, for example, into the shape of a vane airfoil. A superalloy that contains no oxide strengthening particles shows a rapid drop off in 100-hour rupture strength with temperature and very low strengths beyond about 900° C (1800° F). The same alloy with the finely divided oxides present, maintains a reasonable strength to temperatures approaching 1100° C (2200° F).

As an alternative to developing higher and higher use-temperature metals, we are also developing ceramic coatings that insulate the surfaces of aircooled metal components from the very high temperature combustion gases (ref. 3). Using the coating application process called plasma spraying (see fig. 4), we first deposit an oxidation resistant bond coat to the metal blade, vane, or combustor then an overcoat of zirconium oxide to which small amounts of yttrium oxide have been added to make the ceramic more resistant to thermal cycling. In the presence of high-temperature gases a layer of this zirconium oxide only 250 to 375 micrometers (0.010 to 0.015 in.) thick can lower the metal temperature of an air-cooled component by 50° to 100° C (100° to 200° F) or more. Such coatings are good reflectors of radiation and thus lower the radiant heat transfer to the components as well. In addition, the ceramics have the potential for improved resistance to high-temperature corrosion. Although figure 4 shows the coating being applied manually, Lewis is currently developing an automated system that not only will uniformly and reproducibly apply any thickness of coating to any point on the airfoil, but will also measure the coating thickness and tell itself what areas are thin and require additional coating to meet specifications.

For higher temperature applications there is considerable interest in the use of ceramic parts. Figure 5 is a schematic of an automotive gas turbine in which the ceramic combustor, power turbine,

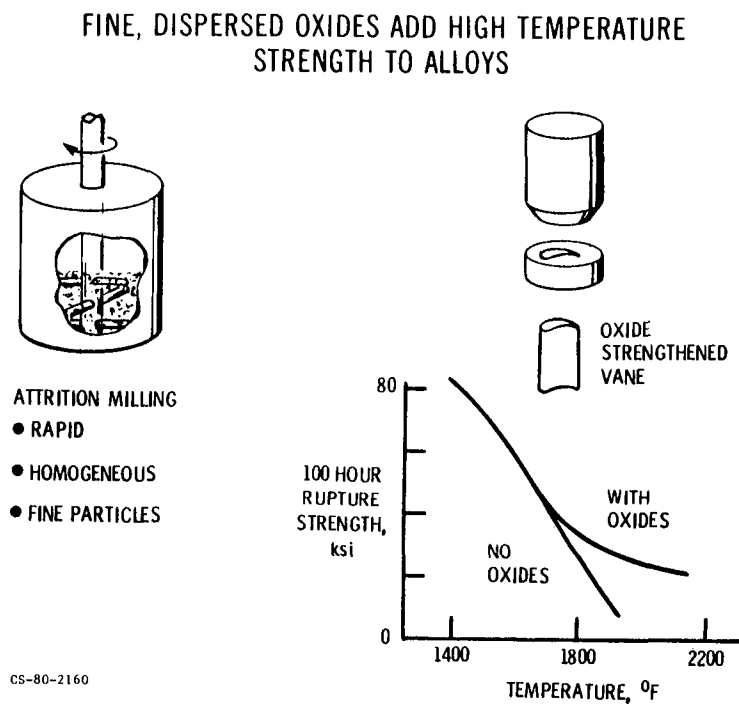


Figure 3

CERAMIC COATING PERMITS LOWER METAL TEMPERATURES

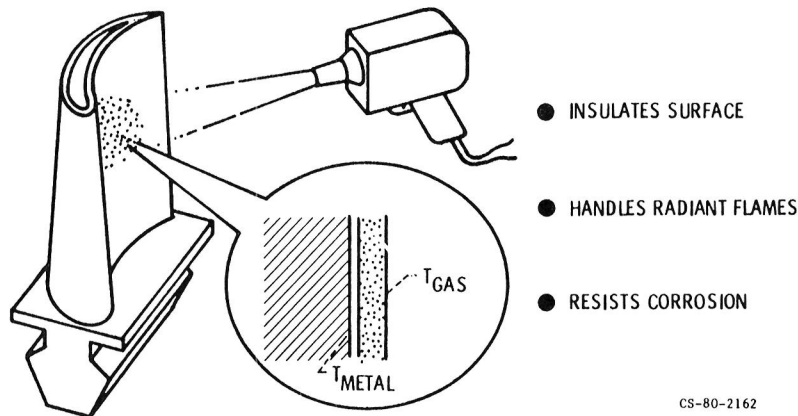


Figure 4

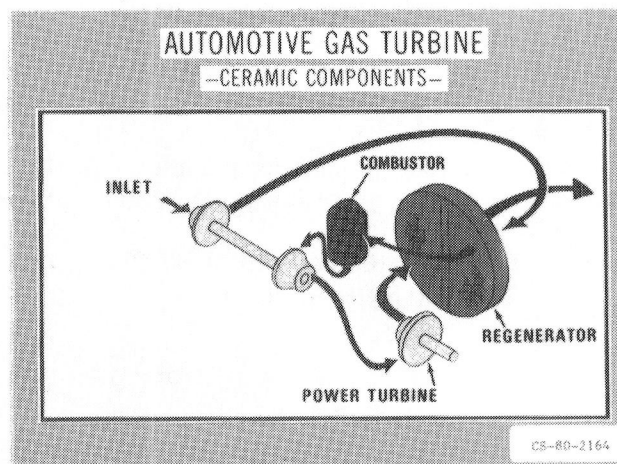
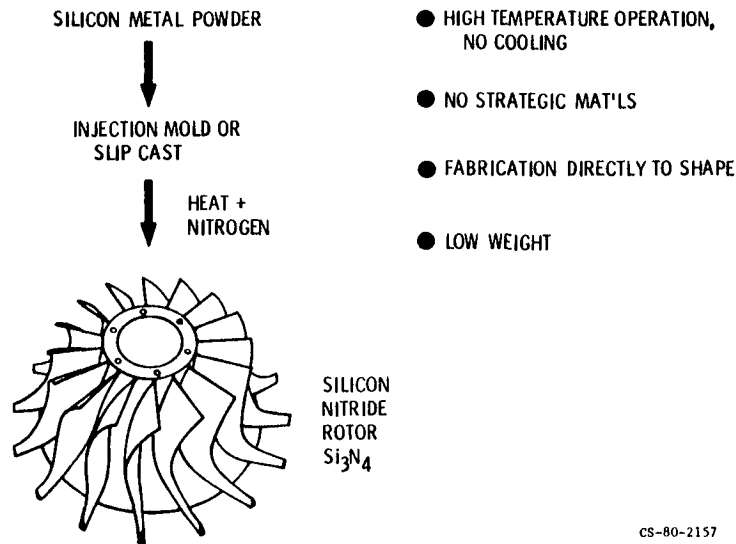


Figure 5

and regenerator are shown. For the automotive gas turbine to significantly exceed the performance capabilities of current internal combustion engines, such parts will have to operate at temperatures beyond the capability of superalloys. In addition, ceramic parts of very complex geometry must be capable of being fabricated inexpensively and in large numbers. While most of the Lewis materials effort for automotive gas turbines is described in another paper at this conference, the significant materials research and development activity here in that research area is exemplified by the development of the silicon nitride automotive turbine rotor. Here, silicon metal powder is mixed with a binder and injection molded or slip cast to a very complex shape (fig. 6). The casting is then heated in nitrogen, whereupon the silicon reacts with the nitrogen and forms silicon nitride (Si_3N_4), a high-temperature ceramic (ref. 4). There is very little dimensional change on firing, so the final part requires little or no finish machining. The use of ceramics like silicon nitride allows high temperature operation without cooling air, thus leading to significantly reduced component complexity. The low density of ceramics minimizes operating rotational stresses and total system weight. Also, such components use no strategic materials, and, if they can be developed, will help the United States minimize its dependence on foreign sources of critical elements.

AUTOMOTIVE GAS TURBINE CERAMIC ROTOR



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Figure 6

Composite Materials

Composite materials exist in our daily activities in many forms: from reinforced concrete, to fiber glass boats, to steel belted tires, to “graphite” skis and golf clubs. However, few of these applications reflect the full capabilities of the advanced composite materials that have been developed in the aerospace industry during the past two decades. On a pound-for-pound basis these materials are stronger and stiffer than steel. Their use permits the fabrication of high performance structures that could not be considered with conventional materials. Some examples of advanced composite material uses are shown in figure 7. Although most modern aircraft use composites for selected secondary structures (fairings, flaps, interiors, etc.), the military jet shown (AV8B Advanced Harrier) is the first high-performance plane to fly with all composite wings (29 percent of the plane’s structure will be composite). The engine shown in the lower left-hand corner is the QCSEE, or Quiet, Clean, Short-Haul, Experimental Engine. QCSEE demonstrates the potential for composites in flight quality hardware. Composites comprise 33 percent (by weight) of the QCSEE structure in a variety of components. Finally, the need for more fuel efficient cars has become more apparent to all of us. The “lightweight concept vehicle” built by Ford (lower right) demonstrates a viable approach to reducing the weight of the full-size car by replacing all of the major structural components with composites. (In this demonstration a net decrease in weight of 560 kg (1250 lb) was attained.) All of these applications reflect activities aimed at improved performance coupled with significantly decreased weight. When fully developed, such approaches can provide better fuel efficiency or greater payload. The following review of some basic concepts of composite materials will show how Lewis is expanding the technology of composites for use in even more demanding applications. The inset in figure 8, a cross section of a fiber-reinforced composite material, indicates the basic features of a composite: a laminar array of fibers in a supporting matrix. This concept can be used in many variations, including orienting selected plies (laminae) in different directions, using woven cloth or multifiber rows rather than single fibers, etc. The desirable structural properties of composites are due primarily to the strengths (greater than 3000 megapascals (500 000 psi)) and stiffnesses (greater than 300 000 megapascals (50 million psi)) of the high performance fibers now available. These factors are most evident in modern graphite fiber composites that combine the remarkable properties

APPLICATIONS OF ADVANCED COMPOSITES

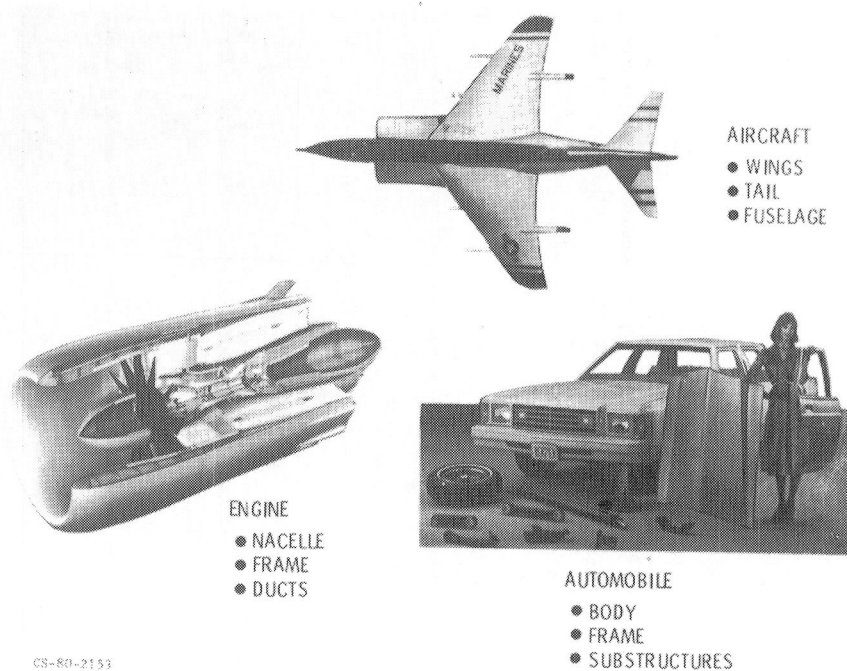


Figure 7

MATERIALS FOR ADVANCED COMPOSITES

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FIBER	MATRIX	APPROXIMATE TEMP. CAPABILITY, °F
GLASS GRAPHITE ARAMID	EPOXY POLYIMIDE	300 600
BORON GRAPHITE ALUMINA	ALUMINUM TITANIUM	600 1000
TUNGSTEN GRAPHITE SILICON CARBIDE	SUPERALLOYS GLASS/CERAMIC CARBON	~2500 ~3000 >3000

Figure 8

of very low density graphite fibers with organic or metallic matrices. Most of the applications shown in figure 7 are graphite fiber epoxy matrix composites.

Polymeric matrix materials have been predominantly employed because of their low density and convenient processability. A wide variety of polymers are used. The first two examples shown (epoxy and polyimide) reflect the use temperatures of interest in aerospace applications. The emphasis on propulsion systems at Lewis has led to the investigation of several such composite systems for applications in the 300° C (600° F) range and beyond. Graphite/polyimide composites have received

major emphasis among the polymer systems; boron/aluminum is a prime contender for lightweight intermediate temperature applications among the metal matrix materials; and tungsten/superalloy composites are being investigated for high strength, high temperature turbine applications. Thus, composites can be tailored to the needs of most applications on the basis of strength and stiffness as well as on the basis of use temperature.

Figure 9 lists some of the major benefits that can be derived from composite materials. Foremost are high strength and/or high stiffness at relatively low weight compared with conventional materials. The bar charts at the right show properties for two composite systems and for steel and aluminum. The fourfold advantage of unidirectional graphite/epoxy over these metals is clear. As noted, these properties can be tailored to the needs of specific structures by orienting fibers in the direction requiring strength or stiffness. Also, many composites offer improved corrosion resistance when compared with conventional materials and, as in the commercial plastics industry, many composite designs offer one-step processing of complex structures having integral stiffeners, fasteners, etc. This aspect (as well as other material and processing factors) can provide lower production costs for the composite component.

Research at Lewis has focused primarily on the polymer matrix composite systems of high temperature capability. The development of a high-temperature matrix resin designated PMR-polyimide (refs. 5 and 6) led directly from that research. This polymer, now commercially available, has been very successfully fabricated into low void, complex-shape composite structures for use at temperatures to 300° C (600° F). Figure 10 shows how PMR composites are produced. Graphite fibers are passed through a monomer solution (melt impregnation is also used). Polymerization is carried out on the fiber (in situ); individual plies are cut and stacked in selected orientations. These plies are then pressed in a die near 300° C (600° F) into airfoil shapes. The PMR system has demonstrated improved performance in the production of flight quality hardware and improved processability, both of which promise reduced production costs for appropriate applications.

The PMR polyimide matrix resin is being used in many applications that benefit from the lightweight high strength aspects of graphite/polyimide composites and require operation near 300° C (600° F). Figure 11 shows some typical applications of the PMR polyimide system. Major applications are on aircraft engines. The development of the graphite/polyimide duct for the QCSEE engine (fig. 7) provided the technology base for the production of a large outer duct for the Navy fighter engine shown here. Beyond the significant weight saving is a substantial cost saving based on the difference in the projected fabrication costs of the PMR duct and the original titanium duct. A

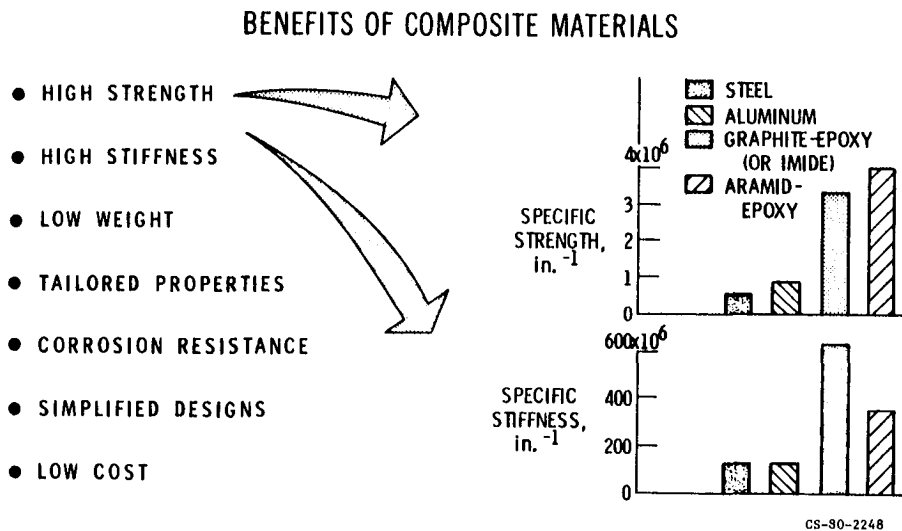


Figure 9

PMR-POLYIMIDE TECHNOLOGY DEVELOPED AT LEWIS

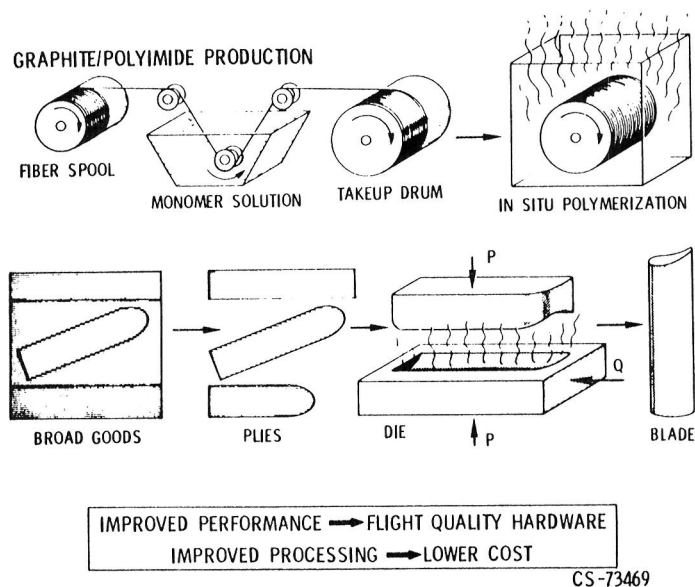


Figure 10

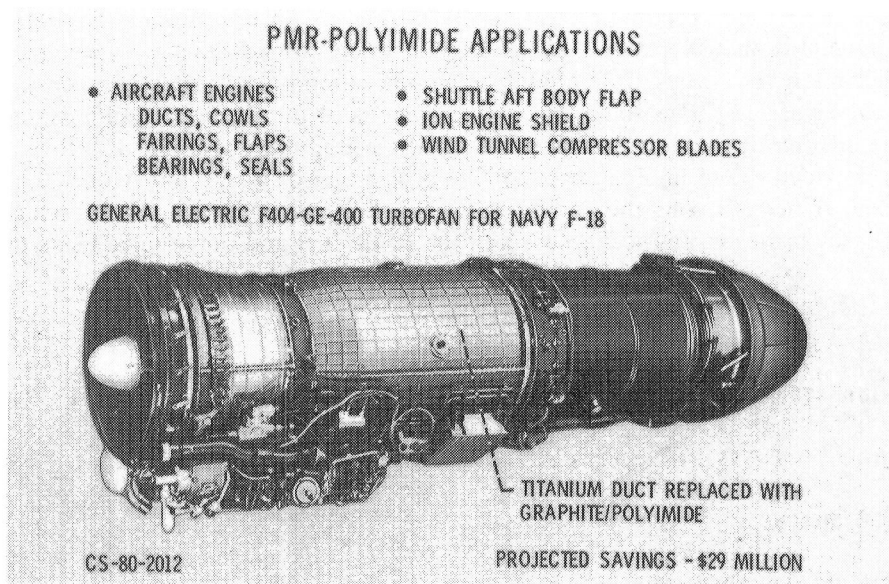


Figure 11

variety of other engine components have been produced or are being considered for production. Potential spacecraft applications have been demonstrated for the NASA Space Shuttle and for ion engine hardware. In another aspect of aeronautics research, an extensive set of large compressor blades has been fabricated for use in a major wind tunnel facility.

NASA is also concerned about limitations in polymer matrix composites. Because these materials are flammable, methods are being developed to minimize the flammability of the polymers and to

IMPROVED FIRE RESISTANCE OF POLYMER MATRIX COMPOSITES

- NEW CURE AGENT DOUBLES INSULATING CHAR YIELD
- BORON ADDITIVE FORMS GLASSY SEAL

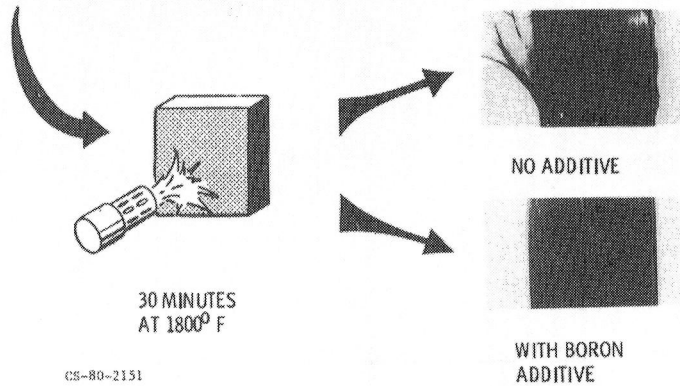


Figure 12

minimize the loss of matrix and fibers in a fire situation. Two examples of this work are shown in figure 12. In one approach, a new cure agent doubles the insulative char formed when a conventional aerospace epoxy composite is exposed to a fire. Thus a minimal change in current materials and processes produces a significant improvement in fire resistance. A second approach involves the addition of boron powder to the matrix material. The boron forms a glassy surface layer during exposure to fire, thereby minimizing the loss of material and maintaining structural integrity even under conditions (30 min at 1000° C (1800° F)) simulating a jet fuel fire.

The applications discussed above represent low or moderate temperature areas of aircraft engines. The applications are varied (besides those noted in figure 11, there are fan containment systems, sound suppression systems, compressor vanes, engine nacelles, and more), but they do not address several major engine components. Significant gains in engine performance can be made by using lightweight high performance materials in rotating components such as fan, compressors, and turbines, and, as mentioned earlier, increasing the turbine operating temperatures is desirable as well. These are all very challenging materials problems, but composite materials are being evaluated which show exceptional promise for such applications.

The requirements for rotating components are particularly stringent because such components must survive the high-velocity impact of runway debris, ice, birds, etc., which may be injected into the engine (primarily during takeoff and landing). At Lewis substantial gains have been made in the production of improved lightweight boron/aluminum composites for impact tolerant structures (refs. 7 and 8). Figure 13 shows a bar chart of impact strengths for notched, unidirectional, composite specimens (made using early fabrication technology (c. 1974)), for titanium alloy specimens, typically used for fan blades, and for an improved composite incorporating large-diameter boron fibers, a more ductile aluminum matrix, and a more carefully controlled production process. Note the fourfold increase in impact strength for this optimized materials system. Although composite fan blades (as shown at the right in this figure) have been fabricated, further design and process development is needed to achieve the required impact properties in these more complex structures.

Finally, another area of advanced, high temperature composite materials development involves the fabrication and evaluation of fiber-reinforced superalloys for very high temperature applications (ref. 9). Composite materials offer significant advantages for such high temperature components because they exhibit exceptional strength at temperatures well beyond the capability of conventional

TOUGHER BORON/ALUMINUM COMPOSITES FOR FANS AND COMPRESSORS

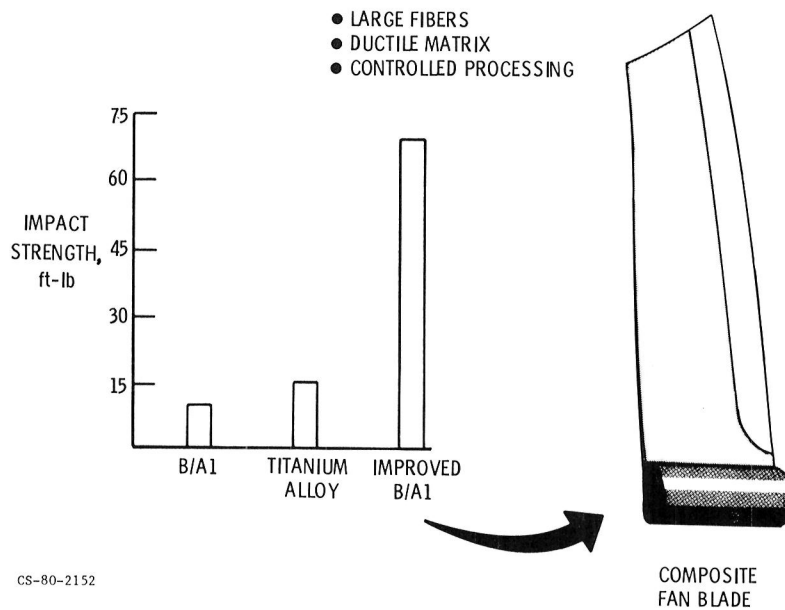


Figure 13

HIGH TEMPERATURE COMPOSITES FOR ENGINES

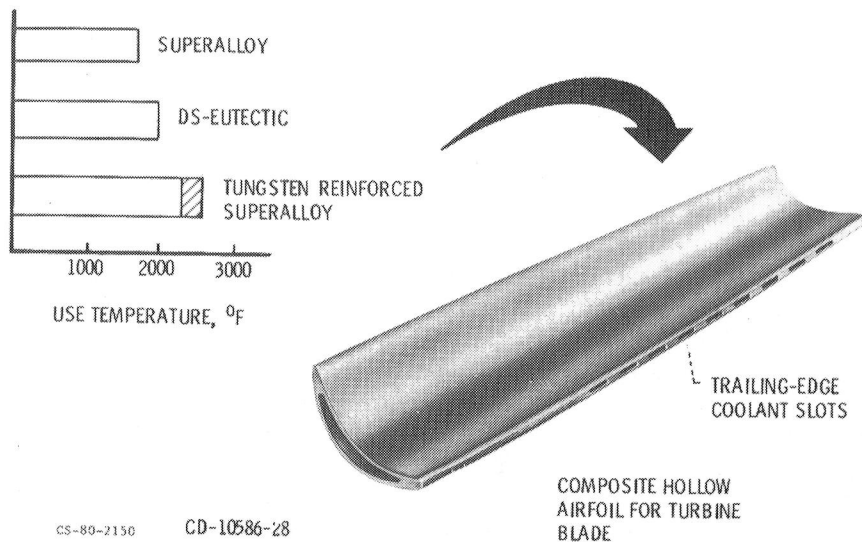


Figure 14

superalloy materials. The bar chart in figure 14 compares the use temperature of a conventional superalloy (1000° C or 1800° F), a directionally solidified eutectic (1100° C or 2000° F), and a tungsten-fiber-reinforced superalloy composite (1200° C or 2200° F for a current superalloy matrix). The shaded area indicates the potential for increased temperature using advanced superalloy

matrices. The photograph at the right shows a hollow airfoil shape which was successfully fabricated from tungsten wire reinforced superalloys.

Composite applications are rapidly expanding in aerospace hardware in a vast array of general purpose items. Advanced composite materials offer some exceptional benefits and, as material and processing costs continue to be reduced, these materials will find their way into a wider variety of commercial products.

Advanced Design and Life Prediction

As better materials come into use, they are often pushed to the limits of their capabilities. Any material used severely enough will, of course, fail. For example, the older bridges in the Cleveland area, like turbine engine parts, follow a failure curve such as shown in idealized terms in figure 15.

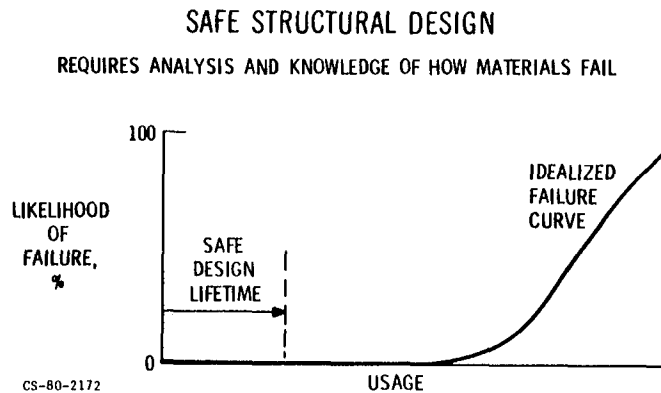


Figure 15

The likelihood of failure increases as the usage increases. In order to avoid unexpected failures, we must be able to accurately calculate a safe structural design lifetime in advance of service. This ability requires several important ingredients. One of the most important ingredients is the ability to analyze and calculate the magnitude of the stress and strain at the most critical location in a component part, since it is the critical local condition that is the origin of failure. Mechanical failures occur either because the stresses and strains are too high, or because the part has a region of unintentionally low weakness. The process of assessing structural lifetime in advance of service, called design by analysis, is graphically described in figure 16. This approach is mandatory for expensive, complex, long lead-time structures for which the old concept of "build 'em and bust 'em" is an impossibility. By combining a model of the component geometry with the material's properties and the anticipated use conditions and by adding a little past experience, one can conduct a structural analysis for the local stresses and strains that will indicate the potential material failure modes. And, based on those modes, one can then calculate a safe design lifetime.

In the area of structural analysis Lewis is both a user and a developer of finite-element computer programs. Two such programs are shown in figure 17. The MARC program is used at Lewis for the analysis of high temperature thermal fatigue problems (refs. 10 and 11). In MARC small, finite elements, or building blocks, are used to represent the turbine blade of interest, rather than treating such a blade as a continuum that would require an infinite number of locations of stress and strain to be calculated. The program calculates the stress and strain on each of these building blocks in terms of the applied mechanical and thermal loads. NASTRAN (ref. 12) is the NASA-developed finite-element computer program which is used for either small or large structures. In NASTRAN the building blocks can take on the appearance of the actual structural members. NASTRAN was used to

DESIGN BY ANALYSIS

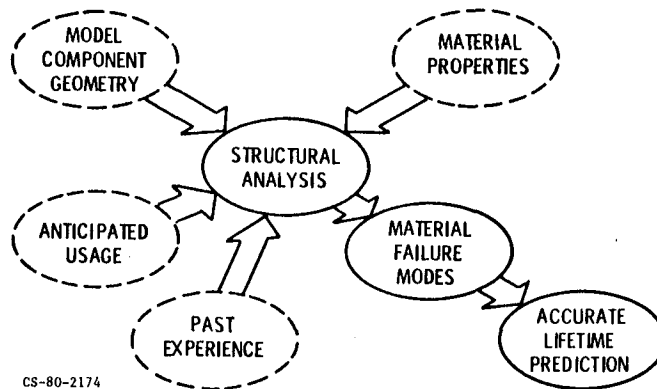


Figure 16

FINITE ELEMENT COMPUTER PROGRAMS

IDENTIFY CRITICAL STRESS LOCATIONS

MARC - TURBINE BLADE

NASTRAN - WIND TURBINE TOWER

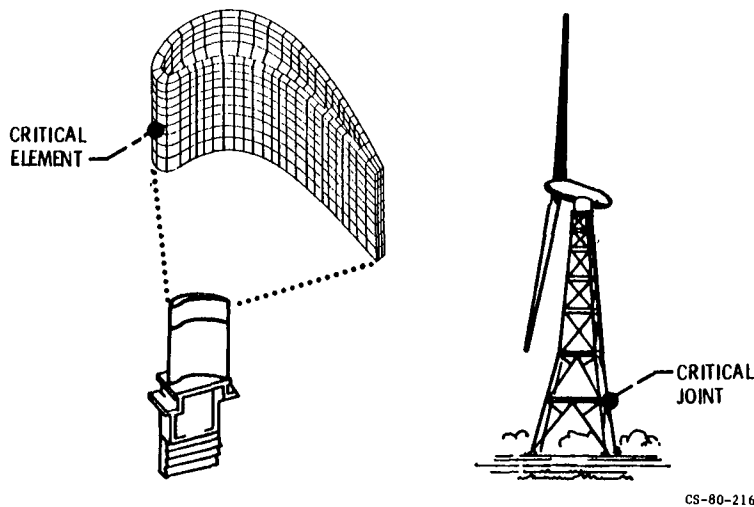


Figure 17

calculate the loads carried by a wind turbine tower (ref. 13) at each structural joint. The crucial joint, that is, the one carrying the greatest load was thus located. NASTRAN has, of course, been used in countless other applications over the years including the designing of composite structures, automotive bodies, etc.

Now let us examine, briefly, how materials fail in gas turbine engines. Fatigue crack initiation, propagation, and ultimate fracture result from the application of cyclic stress and strain. Fatigue cracks initiate at localized microscopic inhomogeneities in the material. Continued cycling causes the crack to grow and propagate deeper and deeper until a critical length is reached and catastrophic fracture suddenly occurs. Creep rupture is a high temperature failure mode. Creep rupture occurs when a substantial load is applied to a material. Thermally activated diffusion mechanisms cause the

material to stretch; that is, it creeps, until it thins down or cracks to the point where it can no longer carry the applied load. A rapidly rotating turbine blade, for example, is subjected to creep due to the high centrifugal loads at high engine operating temperatures. Environmental attack is also a serious failure mode at high temperatures. Here, the elements in the gas turbine environment combine chemically with the metallic surface to form undesirable products. This depletes the material of strengthening elements, and, because the cross-sectional dimensions are decreased as the depth of attack proceeds, the available load-bearing area can be substantially reduced. Finally, we get to a prevalent failure mode in gas turbine engines, and one which is highly complicated because it comes about as a consequence of the simultaneous action of fatigue, creep, and environmental attack. This combination of attack modes is called thermal fatigue. The cyclic action, which is associated with the fatigue contribution, is imposed by the start-stop, heat-up-cool-down operation of an engine. The differential expansion produced by temperature gradients within a material causes self-imposed cyclic stresses and strains. Thermal fatigue cracking or heat crazing is also encountered in such diverse situations as high temperature forging dies, and automotive exhaust valves.

Once we know how materials fail, we must then become quantitative and calculate how long it will take before failure occurs. Each of the failure modes described in the previous figure has been addressed by Lewis engineers, and numerous life-prediction methods have been developed. A rather simple but highly useful method, called the method of universal slopes, has been developed at Lewis (ref. 14) to estimate material fatigue crack initiation resistance. This method can be used without having to conduct a single fatigue test. The required input comes from the properties measured in a tensile test. The required properties are the ductility, D (based on reduction of area), which governs low cycle fatigue resistance in the range from 1 to about 1000 cycles to failure, and the ultimate tensile strength, σ_u , and the modulus of elasticity, E , which govern the life, N_f , in the 1000 to 1 million cycles to failure range. The equation of universal slopes relates the cyclic total strain range, $\Delta\epsilon$, to the fatigue life, N_f , as shown,

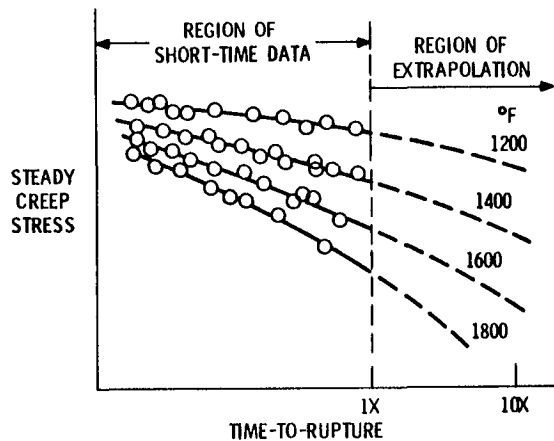
$$\Delta\epsilon = 3.5 E^{\sigma_u} N_f^{-0.12} + D^{0.6} N_f^{-0.6}$$

The chief advantage of the method is its low cost, and, in fact, handbook values of tensile properties can be used to estimate fatigue properties in the early stages of design. The accuracy is approximately plus or minus a factor of five in life. This is usually considered acceptable considering the large degree of scatter associated with the inhomogeneous fatigue process.

Lewis engineers have also made important contributions in the area of describing and predicting the lifetime of materials containing fatigue cracks or flaws, that is, the time the material can be used before catastrophic failure results. This area is called fracture mechanics. At Lewis we have derived accurate equations (refs. 15 to 17) for the stress field surrounding the tips of cracks in loaded structures. We have also contributed to the development of new calculational techniques (ref. 18). The quantity used to describe the stress field around a crack is called the stress intensity factor, K_I , which is used to relate the applied load, crack length, and other geometric factors that contribute to the crack tip stresses. We have applied fracture mechanics concepts to predict the rate of cyclic crack propagation in aerospace structural components (ref. 19). The primary purpose is to calculate the remaining safe lifetime available to any part before it must be removed from service. Finally, Lewis, in conjunction with other research organizations and the American Society for Testing and Materials, has contributed significantly toward the development of standardized tests (ref. 20) for measuring the fracture toughness K_{Ic} of cracked materials.

Several approaches have been developed at Lewis for predicting the lifetime of materials used at high operating temperatures. An example of these is the time-temperature computer program called MEGA (ref. 21). MEGA is the most recent of a long line of time-temperature-creep-rupture parameters that we and others have developed. MEGA enables us to estimate creep-rupture life in the long-time region from data collected in more affordable, short tests. The method has been verified to be accurate within a factor of two in lifetime for extrapolations as much as 10 times the greatest life

TIME-TEMPERATURE – CREEP-RUPTURE PARAMETER MEGA



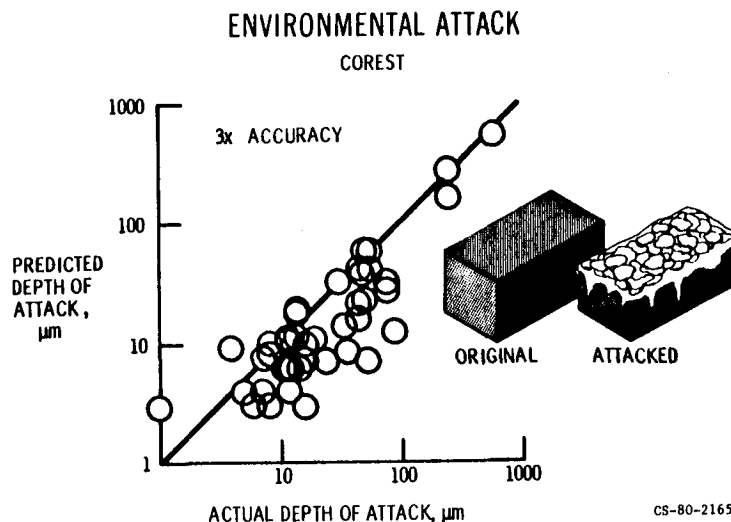
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Figure 18

for which data exist (fig. 18). MEGA, therefore, permits a tradeoff between testing at a low temperature for very long times and testing at a higher temperature for much shorter times. The basic advantage of using MEGA is the cost saving accrued by not having to conduct long and expensive creep-rupture tests. MEGA is the most accurate of any such parameters available today.

We have also developed a new computerized approach for estimating the degree of environmental attack due to hot corrosion and oxidation. This method is called COREST (for corrosion estimation (ref. 22)). Based on measured weight change data, values of attack can be calculated which are accurate to within a factor of 3 in depth over the range from 0.04 to 40 mils (1 to 1000 micrometers). Typical results are shown in figure 19. Efforts are continuing to further improve the accuracy of this life prediction method. The advantage of the approach is similar to that associated with MEGA: cost saving due to the elimination of long-time testing.

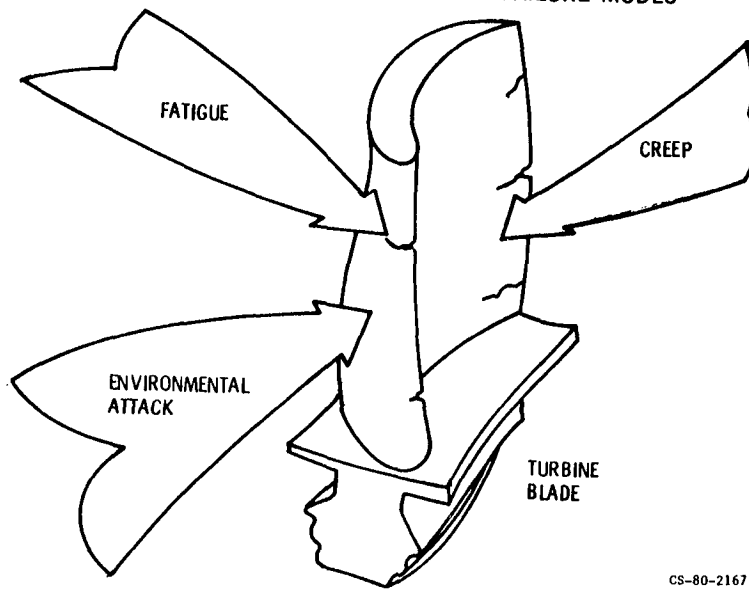
Figure 20 reflects on the fact that thermal fatigue is an interaction of fatigue, creep, and environmental attack, thus making it a complex failure mode. Thermal fatigue life-prediction methods have been developed at Lewis ranging from approximate to sophisticated. An approximate



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Figure 19

THERMAL FATIGUE IS AN INTERACTION OF INDIVIDUAL FAILURE MODES



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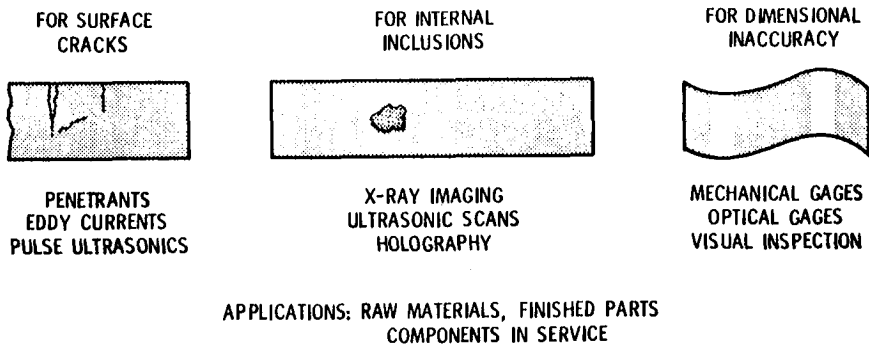
Figure 20

method, called the 10-percent rule (ref. 23), is the simplest to apply but, of course, is the least accurate. It is based directly on the method of universal slopes, discussed earlier and requires only high temperature tensile properties as input. The basic idea behind this rule is that the effects of creep and environmental interaction tend to initiate fatigue cracks much earlier than would normally be required, thus leaving only about 10 percent of the total fatigue life that one would otherwise expect. At the intermediate level of complexity is the time-cycle fractions method (ref. 24). Its application requires a knowledge of a material's fatigue and creep-rupture curves. Both of these types of curves can be estimated by methods previously discussed. This approach is more accurate than the 10-percent rule, that is, a factor of ± 5 on life. A version of this method has been adopted by the ASME Boiler and Pressure Vessel Committee for use in Code Case 1592 for high temperature pressure vessels and piping components (ref. 25). Finally, we have developed a sophisticated method called strainrange partitioning (ref. 26) which permits the most accurate predictions of thermal fatigue life available to date. The accuracy is offset by the fact that specialized laboratory specimen data are required to achieve the ± 2 accuracy. Some techniques for estimating the strainrange partitioning characteristics of a material from a knowledge of tensile and creep-rupture ductility data are, however, under development (ref. 27).

Nondestructive Evaluation

Nondestructive techniques have for years been used to inspect components for cracks, inclusions, and variations in thickness as depicted in figure 21 (ref. 28). Crack inspection has involved such approaches as dye and liquid penetrants, eddy current, and ultrasonics. Inspection for inclusions has primarily been conducted by using X-ray techniques. Thickness variations have been measured by gage blocks, micrometers, and, more recently, a variety of laser and other optical approaches. Such techniques are applicable not only to the raw material prior to manufacture, but also to finished parts and parts that have been in service and require inspection to determine fitness for continued use. As we design components for high performance, we press the usage of materials to their limits. Thus, we

CONVENTIONAL NONDESTRUCTIVE INSPECTION



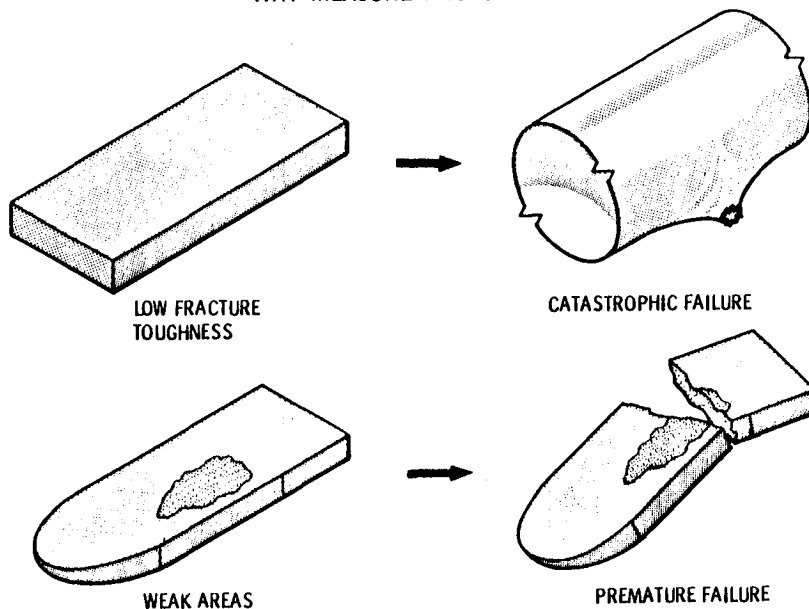
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Figure 21

are no longer concerned with only cracks, inclusions, and variations in thickness, but with the variations in the mechanical properties of the specific materials and components as well. It is quite possible for raw materials and finished parts to have no conventional defects and yet still not be safe. They may have areas of low strength or other poor mechanical properties. Properties that could cause early component failure also include lower fracture toughness in metals, or lower interlaminar shear strength for composites. To conduct destructive tests on all material to be used is expensive, and we obviously cannot destroy a part to find its strength. For these reasons the Lewis focus in nondestructive evaluation is on the determination of specific physical properties, or variations in such properties, within a material or finished part. The concern here is exemplified by the situation depicted schematically in figure 22.

As discussed above, the likelihood of failure is related to usage for the ideal situation. However, in the case of defective or "off-specification" materials, the likelihood of failure increases more rapidly

WHY MEASURE PROPERTIES?



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Figure 22

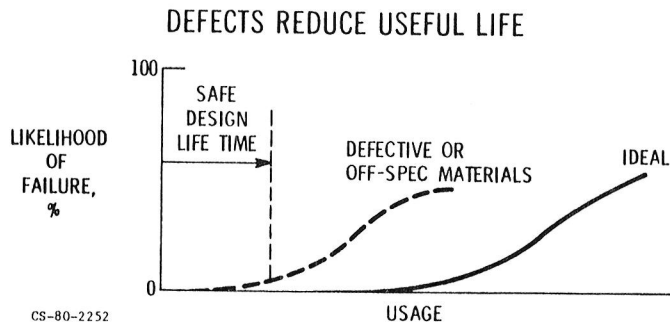


Figure 23

with usage, and safe design lifetimes based on ideal or homogeneous properties are optimistic. Thus, an unexpected early component failure may well result as shown in figure 23. At Lewis we have developed advanced ultrasonic methods with which to evaluate those material variables that govern critical properties. These methods are based on the fact that the microstructure of a material (i.e., the grain size, composite fiber fraction, void content, amount of precipitate present, and other characteristics) controls the way in which materials fail (refs. 29 to 33). As shown in figure 24, these same microstructural factors control the way an ultrasonic wave passes through a material. Thus, by analysis of the changes in ultrasonic waves passing through a material, it is possible to relate a nondestructive quantity to the destructively measured properties. Such an analysis of the ultrasonic waves passing through materials is performed by computer using mathematical equations to derive the quantities required to correlate wave behavior with material properties. Figures 25 to 27 show the laboratory procedure for establishing such correlations (refs. 34 to 37). First, an ultrasonic wave is captured and digitized. The wave is then analyzed to determine what the material microstructure did to the signal. Second, as shown in the left plot of figure 26, mathematical curve fitting establishes the filtering effect the material has on the ultrasonic wave. Such information is used to plot the attenuation of the ultrasonic waves as a function of frequency, as shown in the plot on the right side of the figure. The slope of a straight line fitted to the attenuation curve gives an ultrasonic factor used to predict fracture toughness. For each individual material microstructure, an individual ultrasonic factor is established. By then destructively testing the same specimens on which the varying ultrasonic factors have been identified, a correlation factor, as shown in figure 27, can be established between

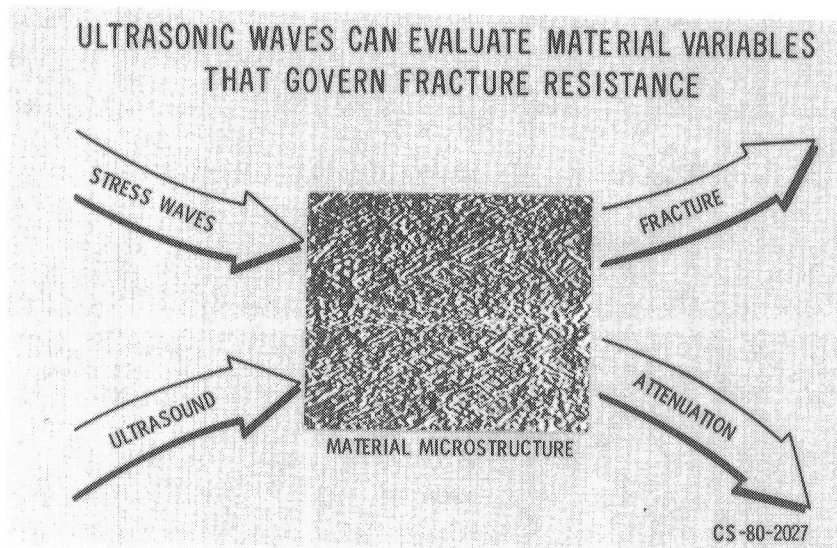


Figure 24

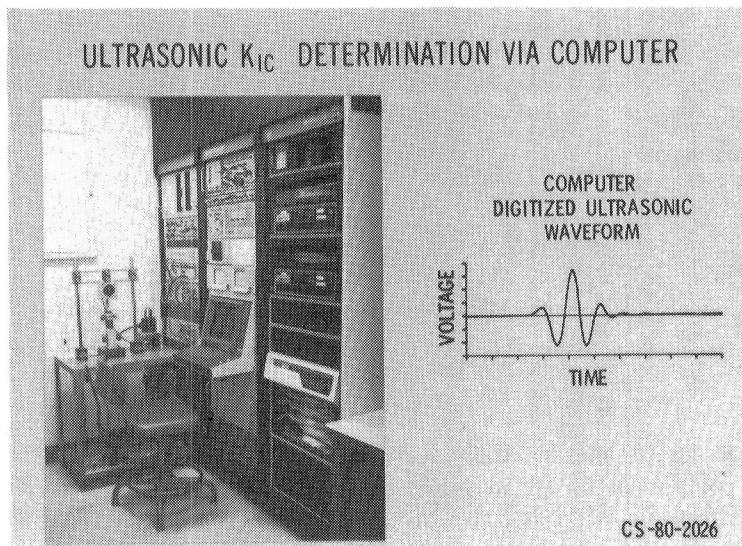


Figure 25

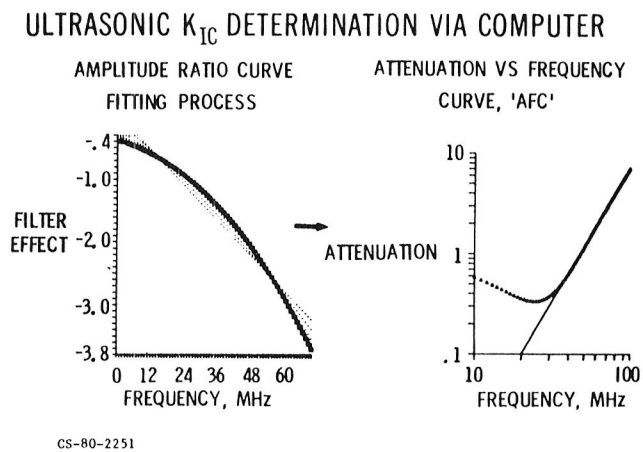


Figure 26

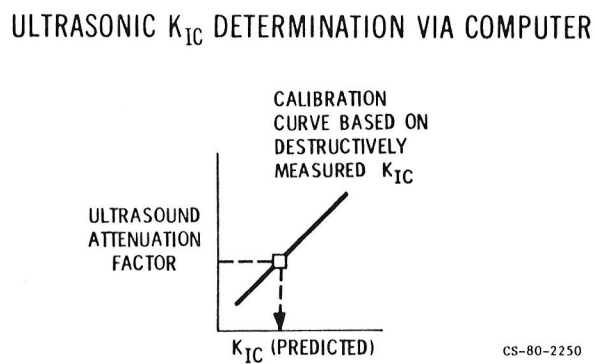


Figure 27

CORRELATION OF ULTRASONIC FACTORS AND CRITICAL STRENGTH PROPERTIES

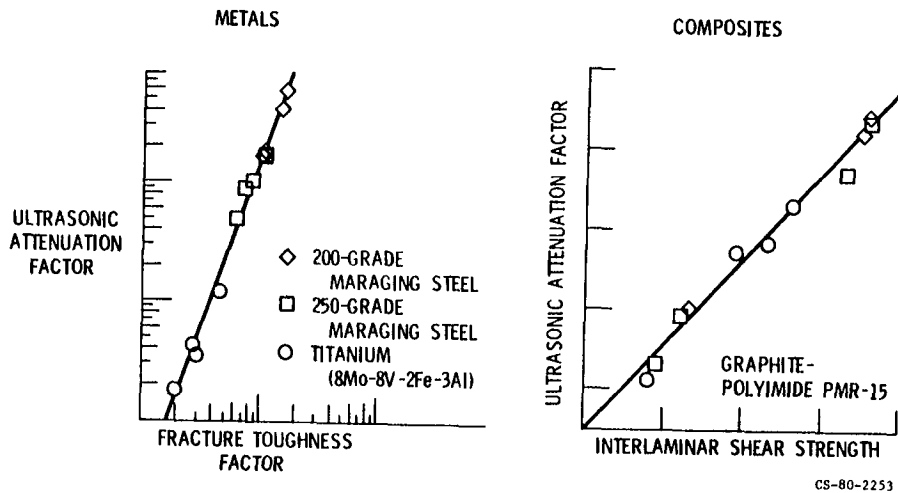


Figure 28

ultrasonic attenuation and the mechanical property of interest. In figure 28 typical correlation plots of ultrasonic factors and critical mechanical properties are shown. On the left ultrasonic attenuation factors are plotted versus fracture toughness. The log-log plots show a linear correlation between these two factors for several grades of maraging steel and for a titanium alloy having aerospace applicability. On the right, interlaminar shear strength versus ultrasonic attenuation is also plotted for graphite/polyimide PMR-15 composites (refs. 38 and 39). Note the linear correlation in this case as well.

The property determination procedure for composites is a derivation of the procedure used for metals. Because of the very heterogeneous nature of composites, an ultrasonic input is used, and the modified signal is received by an acoustic emission transducer (ref. 40). The signal is then analyzed for frequency and energy content. These data are then mathematically transformed into an ultrasonic factor which again can be plotted against the destructively determined mechanical property. The results achieved in figure 28 have been accomplished using a research laboratory facility. In addition to the research described, we are in the process of developing a hard-wired field evaluation device (fig. 29) for determining a specific critical property of a composite in place on an actual aircraft. Such an instrument is needed to monitor the residual properties of the ever increasing number of composites being used in military and commercial aircraft. This field unit will weigh about 15 pounds and will make a single measurement of the response of a composite structure to ultrasonics. The resulting number on a digital display will reflect the effect of the composite microstructure on the ultrasonic wave. This number will have been calibrated against previously destructively determined properties. Thus, the meter can be used to measure degradation of the part as well as the extent of any damage that it has sustained. A laboratory mockup of the portable system was used to map shipping damage that occurred to a Navy S3 aircraft composite spoiler. This technique more accurately mapped the damage than any other existing ultrasonic flaw detection equipment and established the repair feasibility of this costly part. We expect delivery of the first of these field instruments in the next month or so, and verification of instrument accuracy and total capability will be carried out thereafter. If this instrument continues to meet expectations, it is possible that commercial versions of this device will be available in the next year.

FIELD EVALUATION OF COMPOSITES

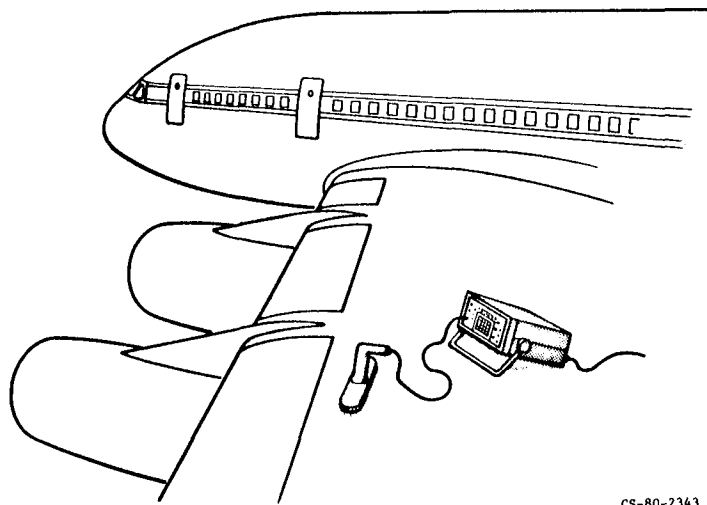


Figure 29

Concluding Remarks

This brief summary of advanced technology being developed by Lewis in four areas of materials and structural design reflects only a portion of the total effort in these areas. Figure 30 highlights items from each area presented. Single-crystal airfoils increase use temperature and are more resistant to thermal fatigue cracking. Composites allow properties of a component to be tailored to best meet the intended application. New life prediction capabilities as well as advanced design tools have been developed. And, in the area of nondestructive evaluation, our technology has extended beyond the identification of flaws and into the area of determining local materials properties with

ADVANCED MATERIALS AND DESIGN

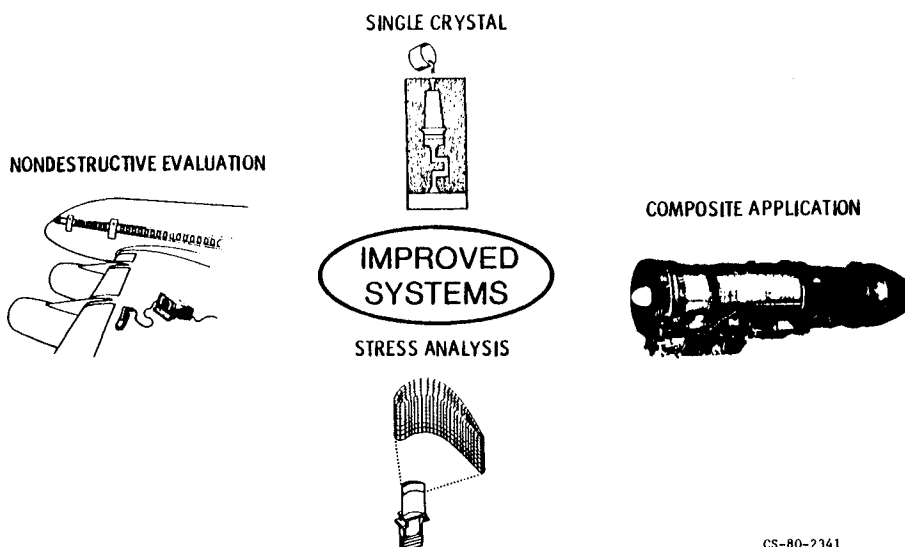


Figure 30

ultrasonic devices. As new ideas, technologies, materials, and analytical approaches are developed, they will be in NASA technology utilization Tech Briefs.

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Thin-Film Coatings

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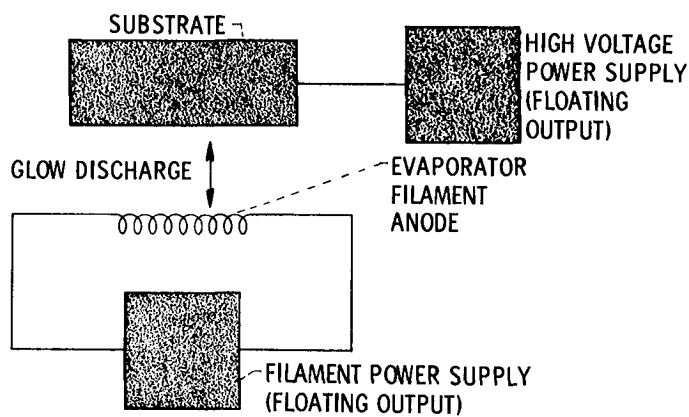
Cleveland, Ohio

Thin-film coatings are used in a variety of industrial and commercial applications, including lubrication, corrosion, catalysis, and decoration. The thin, adherent, high-density films discussed in this paper are applied by the use of two plasma physics techniques: ion plating and sputtering. For those who are unfamiliar with these techniques, I will discuss how each operates, what surfaces can be coated, and what kinds of materials can be applied. The effects these films have on the mechanical and physical properties of solid surfaces will then be discussed.

Ion Plating

Ion plating is a relatively simple, unsophisticated process (fig. 1). One needs a relatively crude vacuum system (of the order of 10^{-5} or 10^{-6} torr) to house the ion-plating process. The essential ingredients or components of the process are the substrate, or component to be coated, and, of course, the coating. The substrate may be a bearing, gear, or seal, a catalytic surface, a surface that requires corrosion protection, or a surface such as the people in the automobile industry are using for decorative purposes, or any other part that needs to be coated. In addition, one must have a high-voltage power supply, so that a negative potential can be placed on the substrate surface, and a filament or heating source to evaporate the coating material. A number of sources can be used for heating the substrate. A filament heat source with a filament power supply can be used or induction

ION PLATING SYSTEM



CS-53520

Figure 1

heating or electron beam heating can be used. Generally, the material to be coated is placed on the filament.

The method for operating the ion-plating system involves evacuating the chamber to a pressure of 10^{-5} or 10^{-6} torr and then backfilling the chamber with argon to a pressure of 10×10^{-5} to 20×10^{-3} torr, generating a negatively charged substrate surface. The positively charged argon ions strike or bombard the substrate surface with considerable energy, knocking off adsorbates and oxides and thereby generating a clean, nascent surface. This cleanliness ensures good adhesion of the coating.

In ion-plating we are restricted to using materials that can be evaporated; this means metals and simple alloys. We evaporate the coating into the glow discharge, that is, the argon plasma. All metals have lower ionization potentials than argon, and as a consequence the metal (or coating) becomes ionized, that is, positively charged. The ions are then carried with the argon ions to the substrate surface where they deposit as a film on the substrate. Because this is a gaseous process, the material is carried to all points on the solid substrate. Because of the negative charge on the substrate, the positively charged metallic ions come in with a potential and bury themselves in the substrate.

The actual ion-plating process of operation is shown in figure 2 which is a photograph of ion-plating taking place. The glow about the substrate surface is due to the argon ions bombarding and cleaning the specimen surface. After the surface has been sufficiently cleaned, we see in the second photograph the filament being heated to incandescence. Metallic ions are evaporated into the plasma and then they are carried with the argon to the substrate surface, coating all points on the solid surface uniformly.

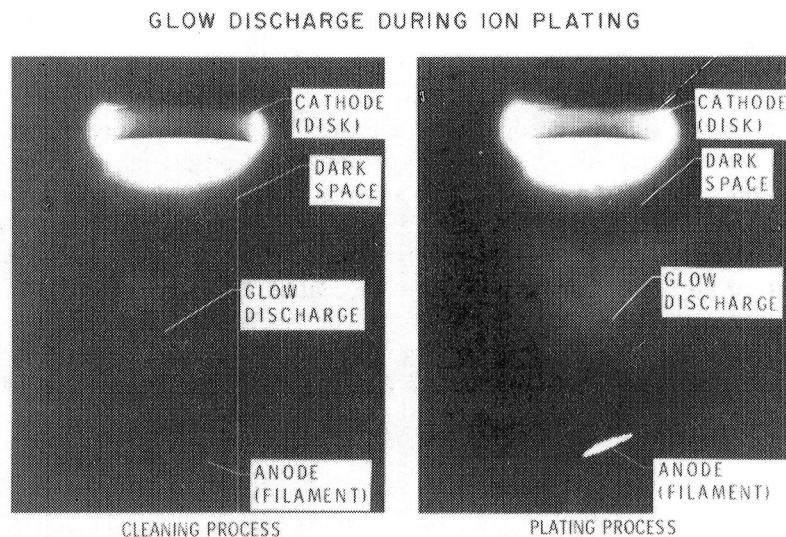


Figure 2

What are the advantages of ion-plating over other processes for depositing thin films?

(1) High kinetic energy of ionized material producing

(a) Sputter etched surface

(b) Graded interface

(2) High nondirectional throwing power, that is, complex surfaces coated

Because of the high energy involved and because of the sputter cleaning, we can actually clean and etch the substrate surface to promote strong adhesion. Because of the potential on the substrate the coating ions are driven into the substrate surface, and we obtain what is referred to as a graded interface. Instead of having a sharp line of demarcation between coating and substrate, we obtain a diffuse or graded interface (fig. 3). As a result of the nondirectional nature of the gaseous plasma, very complex geometric surfaces can be coated very uniformly with thin films. Film thickness can be controlled to 50 angstroms.

ABRUPT AND GRADED INTERFACES

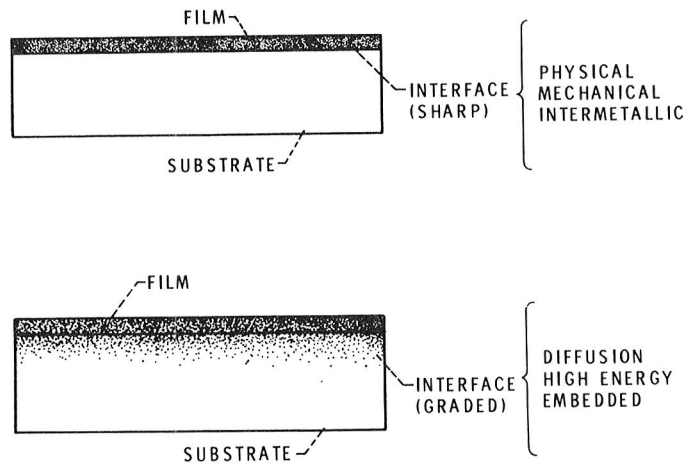


Figure 3

Figure 4 is a photomicrograph of a tungsten surface that has been ion-plated with a nickel film. It is impossible to find the interface, which lies over a broad area. We do not know its boundaries. The photomicrograph shows, essentially, a coating of nickel, a tungsten substrate, and, someplace in between, an interfacial region. There is, however, no sharp line of demarcation between the coating and the substrate.

For many applications this type of interface is ideal because there is no way of mechanically removing the coating from the substrate except by grinding or machining it, and part of the substrate, away. It cannot be removed by conventional techniques or by the mechanical forces involved in practical tribological systems. This is a very desirable interface.

Some of the types of materials that can be coated by ion-plating are shown in figure 5. These are polymer bearing cages, ceramic tubes, and Teflon tubing (coated inside and out with metallic films) and many conventional metal and alloy parts, some with very complex geometries.

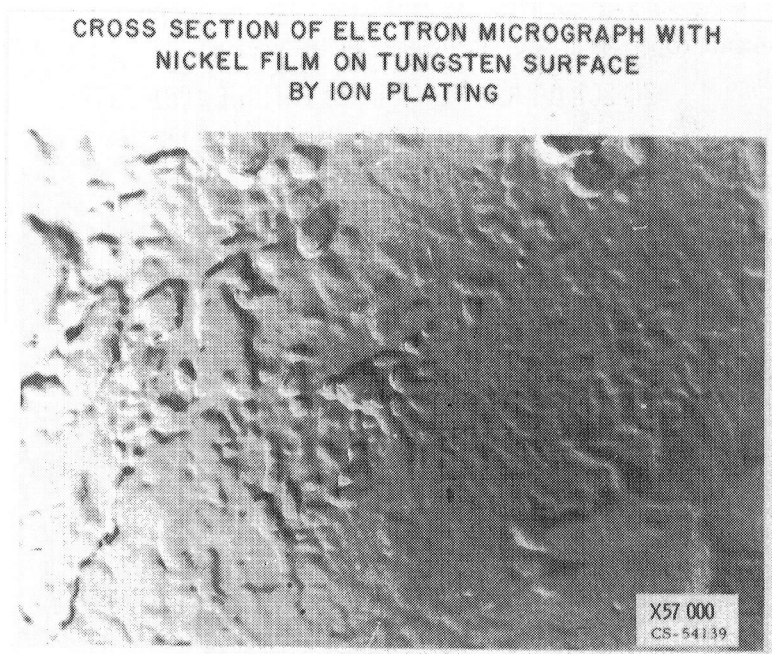


Figure 4

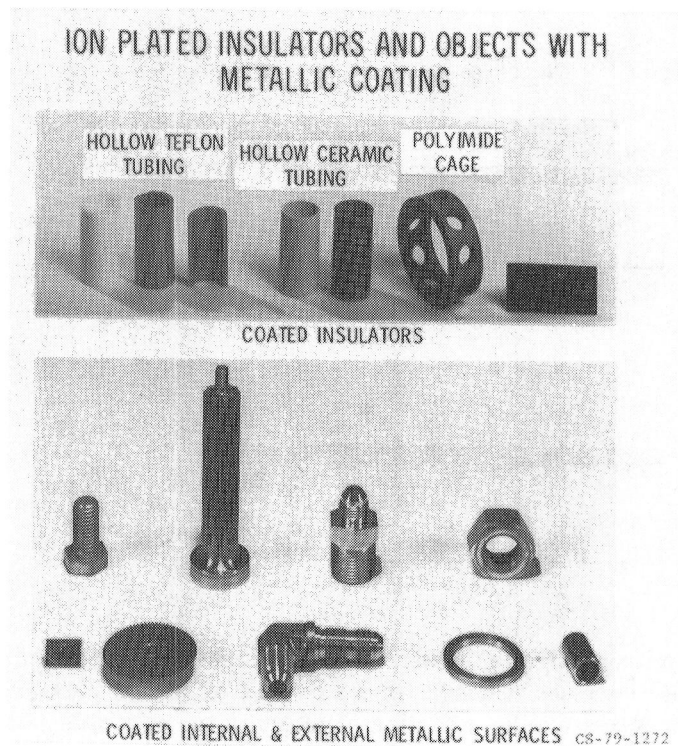


Figure 5

Because of the graded interface and the tenacious bond, the very dense and pore-free coating has a pronounced influence on the mechanical and physical properties of the substrate material. One particular property, for example, so influenced is fatigue life.

The influence of ion-plating on fatigue life is shown in the data of figure 6, a plot of stress as a function of cycles to failure for three sets of data: steels, steels coated with gold by conventional electroplating, and steel coated with gold by ion-plating. Essentially steel and the electroplated steel display no difference in fatigue life: The curve is essentially one for both sets of data. The curve for ion-plated steel, however, indicated a marked improvement in the fatigue life.

Other mechanical properties are also influenced by the presence of ion-plated films. In the area of

EFFECT OF ION PLATING ON FATIGUE PROPERTY OF LOW CARBON STEEL

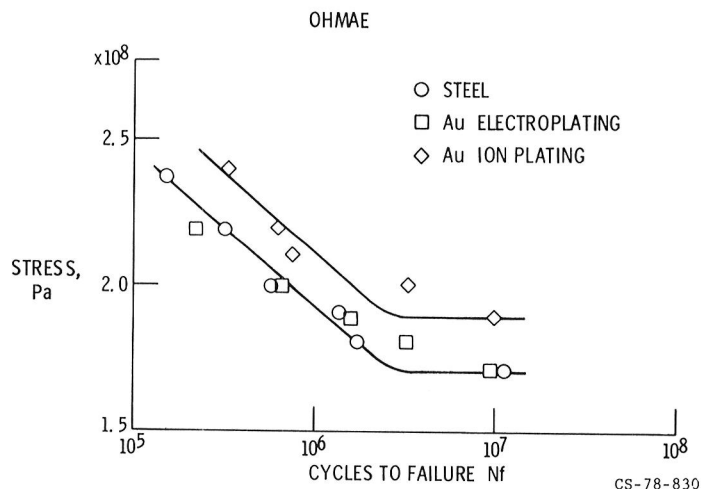


Figure 6

tribological coatings (coatings for lubrication), fantastic improvements are found in lubricating performance by use of the ion-plating technique.

Sputtering

The sputtering process has some similarities to and some differences from ion-plating. Among its features are these:

- (1) Versatility
- (2) Momentum transfer
- (3) Stoichiometry
- (4) Sputter etching
- (5) Target geometries (coating complex surfaces)
- (6) Precise controls
- (7) Flexibility
- (8) Adjustable sputtering rates
- (9) Ecology

One of the best features of the sputtering process, however, is its versatility. We can deposit almost anything on anything; polymers on metals, ceramics on metals, metals on ceramics, metals on polymers—nearly any combination of coating material and substrate material.

Sputtering, like ion-plating, is a momentum transfer process; however, with sputtering the proper compound chemical or atomic ratios can be maintained: In other words, if you wish to deposit a complex compound on a substrate surface, you can do it with the sputtering process.

As in ion-plating, the substrate can be sputter-etched, or cleaned, before deposition to gain good adhesion. The adhesion, however, is not like that obtained with ion-plating, in that sputtering produces a sharp interface. It is a good interface, however, and it forms a very strongly bonded coating to the substrate.

One can have variations in target geometries with sputtering. There is precise control with the process. As in ion-plating, film thicknesses can be controlled to 50 angstroms. It is flexible, in that sputtering rates can be varied to obtain different depositions in various time elements. Ecologically, it is a very clean system; like the ion-plating process, because it is done inside a vacuum.

Just as in ion-plating, a relatively unsophisticated vacuum chamber houses the sputtering process. There are two types of sputtering, dc (direct current) and rf (radiofrequency). Figure 7 happens to depict the rf process. In the vacuum chamber is the target, that is, the coating material and the

SCHEMATIC OF SPUTTERING PROCESS

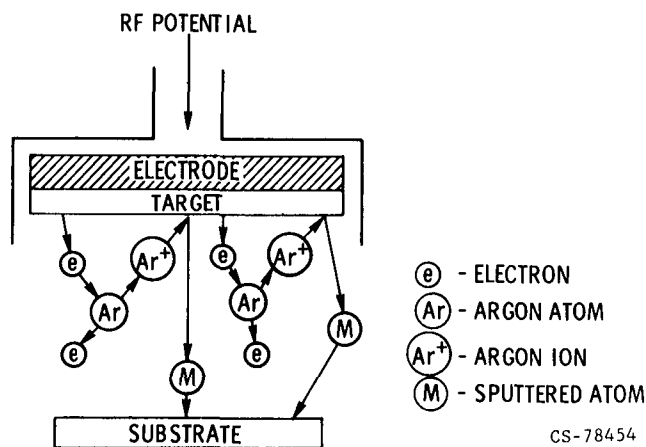


Figure 7

substrate. Into the chamber argon is emitted and positive charged argon ions are generated. A negative charge placed on the target causes the positively charged argon ions to bombard the target and knock material from the target to the substrate surface, thereby applying a coating to the substrate. A preliminary step can be introduced by simply directing the argon ions to the substrate and cleaning it just as is done in the ion-plating process. A very uniform coating on very complex geometric surfaces can be obtained with the rf sputtering process.

Figure 8 reveals the process in actual operation. In the figure the substrate happens to be a bearing cage. The holes are the pockets that hold the ball bearings. A ring has been provided in figure 8 for the sputter cleaning of the substrate surfaces.

As mentioned earlier, sputtering is a very versatile process in that almost anything can be coated with anything. For example, figure 9 shows hypodermic needles that have been coated with a Teflon film. When a needle is injected into the skin it is friction resistance which causes the pain felt. The

RADIOFREQUENCY DIODE SPUTTERING APPARATUS WITH DIRECT-CURRENT BIAS

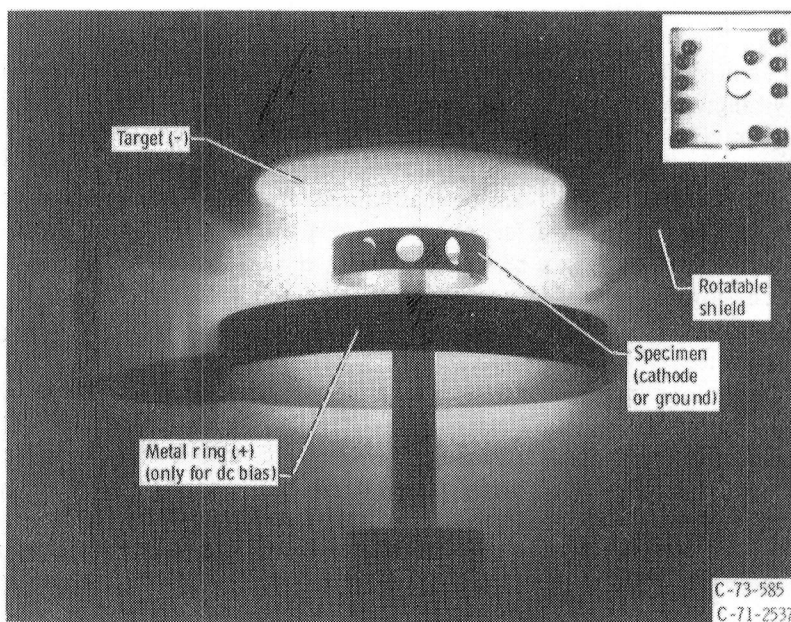


Figure 8

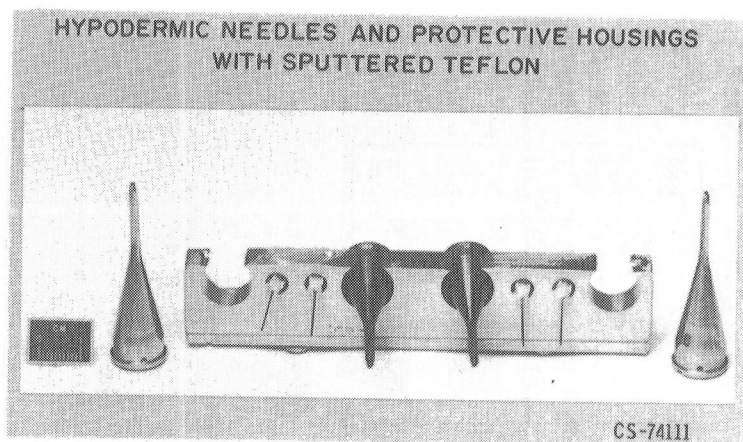


Figure 9

Teflon coating reduces the pain associated with injections by reducing friction. This process was perfected in our laboratory.

The sputtering process is used very heavily industrially. For example, figure 10 is a video record. I am sure most all of you have seen the television commercial for the video records that are currently being marketed. Before Magnavox got into the business, RCA was working on the process. RCA built a vacuum chamber—a very sophisticated system with conveyor belts and interlocks—where two coatings were applied by sputtering. The first coating was a 900-angstrom gold film over the surface of the polymeric record. The second was a 600-angstrom film of molybdenum disulfide for lubricating purposes. Figure 10 is an actual video record with very small fine grooves on its surface, much finer than a conventional audio record. The company intended to commercially produce these records and sell them for approximately \$9.95 a piece. It is a very economically feasible process, using two coating steps in the deposition of the films. Lewis personnel consulted with and provided expertise to RCA personnel in the coating application process.

VIDEO RECORD PREPARED BY SPUTTERING

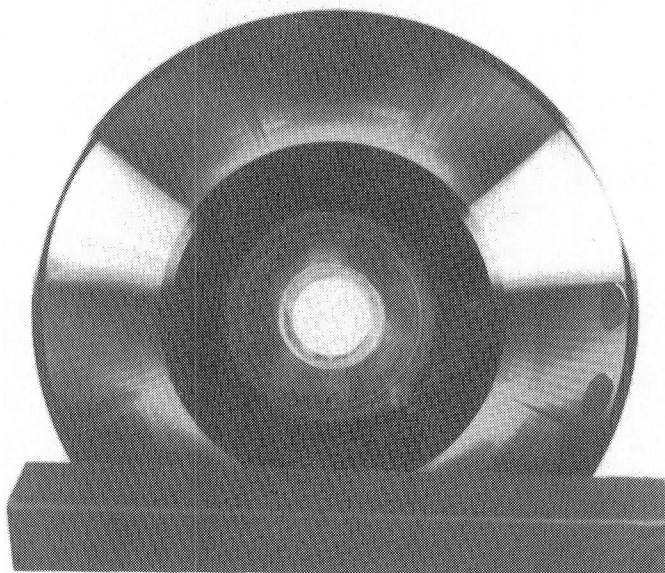


Figure 10

Coating Thickness

While these processes, both ion-plating and sputtering, are used primarily for depositing thin films for corrosion protection, lubrication, decoration, and catalysis, they can be used, particularly the sputtering process, for the deposition and formation of free-standing bodies. Figure 11 is a photograph of a shroud, actually a cylinder, that was formed completely by sputtering. The film thickness was built up enough to form a free-standing body.

Hard Face Coatings

In our own laboratory, one of our current interests in the sputtering process is to develop very hard-face, wear-resistant coatings. Throughout this country and abroad, there is a considerable amount of research effort (in fact, millions of dollars are being spent) to find good, wear-resistant coatings for use in the tooling, drilling, and machining industries. Such coatings would eliminate the need for solid carbide bodies for machining and cutting operations. The use of inexpensive steels with very hard refractory-type carbide coatings would greatly reduce equipment costs.

FABRICATION OF CYLINDERS BY SPUTTERING

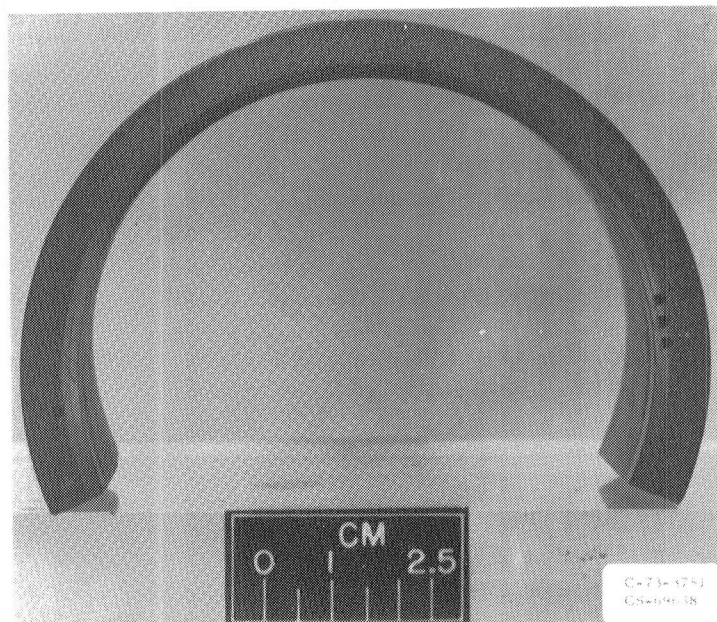


Figure 11

The problem that confronts everyone, however, is getting good adhesion of these hard-face coatings to the substrate. The coating material generally has markedly different mechanical properties from the substrate, and these differences cause considerable stress at the interface. As a consequence, the interface is weak and the coating easily fractures or falls off the substrate.

Researchers here at Lewis, as well as at a number of other places, are exploring ways of improving the adhesion of the hard-face coating to the substrate. One technique that we have developed is the use of an interfacial or transition layer between the substrate and the coating. One suitable transition layer material was discovered to be ordinary oxides. A buildup of selected oxides on the substrate surface before applying a hard-face coating (e.g., refractory metal carbides such as molybdenum, tungsten, titanium) improves adhesion considerably.

Now this is just the opposite of what we discussed earlier. In the deposition of lubricating and corrosion protective film, for example, sputter cleaning and ion-bombardment promote better adhesion. But with hard-face coatings, we deliberately oxidize for the same reason.

In the course of our experimental work, we are interested in the friction and wear of these coatings, and how well do they stand up in mechanical applications. Figure 12 presents some data on a titanium diboride (TiB_2) coating on a 440 C steel substrate. Plotted in figure 12 are the friction coefficient and the wear for the material in four cases: (1) uncoated 440 C, (2) uncoated and oxidized 440 C, (3) coated and etched 440 C, and (4) coated and oxidized 440 C. The best performance was obtained with the coated and oxidized material.

We have in our laboratory analytical surface tools that assist us in what we call depth-profiling, or analyzing, these films. We can start, for example, with X-ray photoelectron spectroscopy (XPS) and analyze the chemistry of the film at the outside surface. Then we can ion-bombard with argon ions knocking away the coating to expose the interface region, and analyze the interfacial region and its chemistry. Going on further through the interfacial region and into the substrate, we can determine the chemistry of the material at any point. We have done this for a number of these hard refractory carbides using the oxide interface.

Figure 13 presents some results for a series of molybdenum compound coatings. The substrate is 440 C bearing steel, represented in the figure by Fe (iron). The coating materials are molybdenum carbide (Mo_2C), molybdenum boride (Mo_2B_5), and molybdenum silicide (MoSi_2). Between the substrate and coating material are the deliberately formed oxide layers.

AVERAGE FRICTION COEFFICIENT AND RIDER WEAR FOR 440C DISKS

LOAD 0.5 NT, 304 STEEL RIDER, COATING TiB_2 (-300 V BIAS)

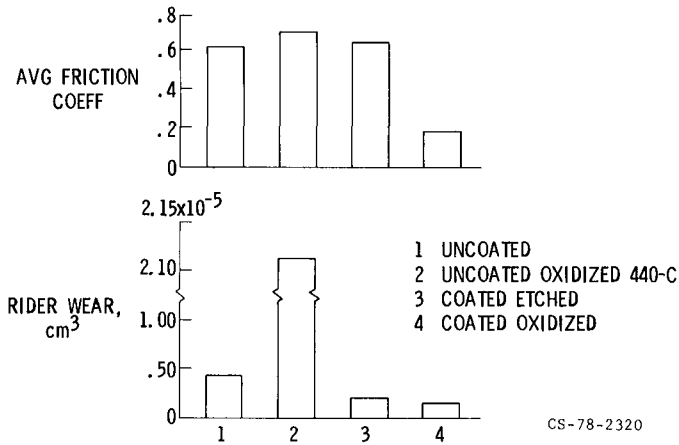
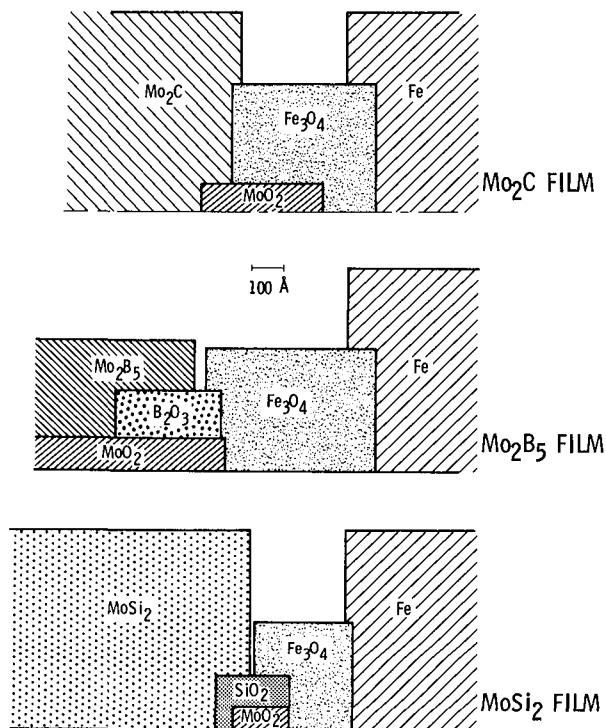


Figure 12

INTERFACIAL REGION OF COATINGS ON OXIDIZED 440C



CS-79-1596

Figure 13

X-ray photoelectron spectroscopy reveals first the molybdenum coating, then the molybdenum oxides, the iron oxides, and finally the iron substrate. (The same thing is true with the boride and silicide, except one sees different oxide compositions.) What the oxides do, then, is key the coating material to the oxide and then the oxide to the substrate, thereby promoting good adhesion of the coating material to the substrate.

We have since found that other materials can be used to achieve the same type of bonding. For example, a layer of pure titanium metal sputter-deposited between the titanium alloy substrate and the coating material bonds very strongly to the oxide of a titanium-base alloy substrate and, for example, very strongly to the carbon of a carbide coating.

Reactive gases, such as acetylene, can also be used to promote the formation of interfacial carbides. These carbides perform the same keying function as oxides, in that they promote the adhesion of the hard, refractory coatings to the substrate.

Conclusions

Sputtering and ion-plating are very useful techniques for applying dense, tenacious films to a variety of surfaces. The distinct advantage of the ion-plating process is the diffuse, or graded, interface it produces; that of sputtering is the wide variety of coating materials that can be deposited on a wide variety of substrates. Both processes have applications in a number of areas, including catalytic corrosion, protective, decorative and lubrication films.

Self-Lubricating Composite Materials

Harold E. Sliney

National Aeronautics and Space Administration

Lewis Research Center

Cleveland, Ohio

The properties that are of primary interest in structural composites are adequate mechanical strength and corrosion resistance. Self-lubricating composites, must also have adequate strength and corrosion resistance. But superimposed on this is the requirement that these materials be self-lubricating. They must have a low friction coefficient and a low wear rate without the aid of oil or grease lubrication.

The two types of self-lubricating composites that will be discussed in this presentation are polymer matrix composites and inorganic composites which contain no polymeric materials at all. I have chosen compositions from each of these types that already have found application in the aerospace industry but that we feel have much more general applicability.

Polymer Composites

Some of the features of polymer-base composites are as follows:

(1) Components:

Polymers

Solid lubricants

Reinforcing agents (fibers)

(2) Methods of preparation:

Injection molding

Transfer molding

(3) Important characteristics:

Nongalling

Corrosion resistant

The typical components consist of the polymer, a solid lubricant material, and reinforcing agents, generally fibers. Sometimes a single component will serve more than one function. For example, in the fairly well-known glass fiber reinforced PTFE (polytetrafluoroethylene) materials, the polymer (PTFE) is both the matrix material and the lubricant. Graphite-fiber-reinforced polyimide (GFRPI) is a particularly interesting composite in which the graphite fibers serve both a lubricating function and a reinforcing function.

Typical methods of preparing polymer-base composites are injection molding and transfer molding. Injection molding is a relatively rapid process in which a completely polymerized material is heated above its glass transition temperature, to cause it to flow readily. It is rapidly injected into the mold, cooled, and the molded part ejected. Polymers that are not thermoplastic, or that have very high glass transition temperatures, are often prepared by transfer molding, in which the partially polymerized (or B-staged) material is introduced into the die cavity and is held there under heat and pressure until polymerization is completed. This is a slower and, therefore, a more expensive process, but it is the one that is used for the preparation of graphite-fiber-reinforced polyimide composites.

Some of the polyimides are thermoplastic, but they require much higher processing temperatures than are generally available in injection molding equipment. The economy of molding the polyimides could be greatly improved by the development of a high-temperature injection molding process for this class of polymers.

An essential characteristic of self-lubricating composites is that they are nongalling; the material must not only have an adequately low wear rate but the wear surfaces that are generated must have an acceptable topography. In other words, the surface must not become rough and must not transfer large amounts of material from one surface to another. In order to maintain proper clearances the surfaces should wear smoothly and if there is transfer from one surface to another, it should be in the form of a very thin film. The composite must be corrosion resistant. Fortunately, polymers are inert in most dry bearing environments. However, some hydraulic fluids and liquid lubricants are incompatible with some polymers. Therefore, care must be exercised in selecting polymer composites where the probability of liquid contamination exists.

A plain spherical bearing with a self-lubricating liner is shown in figure 1. The outer ring of the bearing is sectioned. The liner, about 0.76 millimeter (0.030 in.) thick, is bonded to the inside of the outer ring. The liner consists of GFRPI that has been prepared by transfer molding directly into the

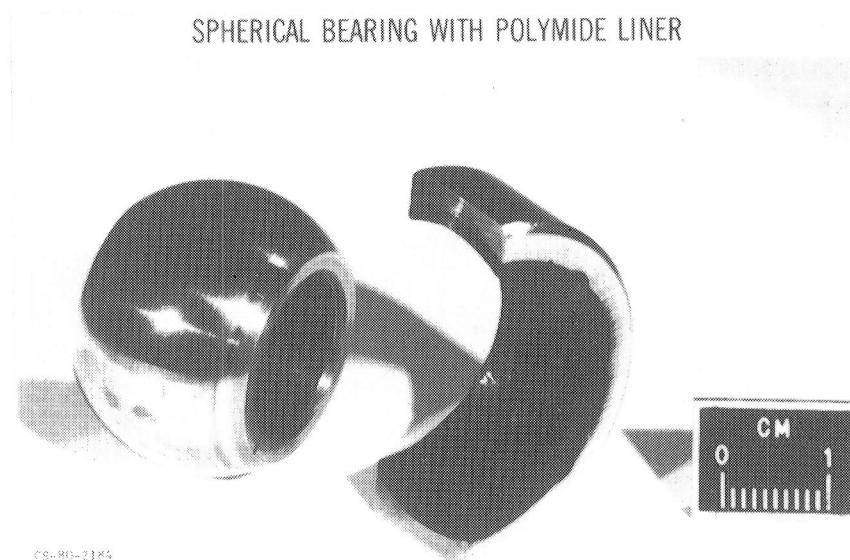


Figure 1

space between the ball and the outer ring. During the molding process, the ball and the ring are located precisely by a fixture in the mold. Some typical mechanical strength properties of a GFRPI material, which consists of a one-to-one ratio by volume of graphite and polymer, are given in table I. This composition appears to be an optimum ratio of fiber and polymer for bearing applications. The compressive yield strength of this material is on the order of 0.2 gigapascal (30 000 psi). The elastic modulus is fairly low, 4.3 GPa (640 000 psi). The thermal expansion coefficient is a little higher than that of most bearing metals, and this must be taken into account in designing the internal clearances of the bearing.

The friction coefficients, and the scatter in friction coefficients, as a function of temperature for GFRPI lined bearings are given in figure 2. The data are for two different designs. In one the ball is molded out of the composite material; in the other (shown in fig. 1) there is a molded GFRPI liner between a steel ball and a steel outer ring. In dry sliding, where no oil or any additional liquid lubricant is involved, a friction coefficient of 0.2 or lower is generally acceptable. Of course, what ultimately determines an acceptable friction coefficient depends on the requirements of the

TABLE I.—ROOM TEMPERATURE PROPERTIES OF 1:1 GRAPHITE
FIBER REINFORCED POLYIMIDE COMPOSITES

Compressive yield strength, MPa (psi)	200 (30 000)
Elastic modulus, GPa (psi).....	44 (640 000)
Thermal expansion coefficient, cm/cm °C (in/in °F).....	25.6×10^{-6} (14.2×10^{-6})

application. In some applications a friction coefficient higher than 0.2 would be acceptable. In other applications a very low friction coefficient on the order of 0.05 may be required. As a general rule, friction coefficients of 0.2 or below are acceptable for dry sliding conditions in self-lubricating bearings. We can see that the friction coefficient is below 0.2 at room temperature and decreases with increasing temperature to about 315° C (600° F), which is quite a high temperature for the use of a polymeric material for any application, particularly for a plain spherical bearing application where a high load capacity or load carrying capability is required.

Another essential characteristic is wear resistance. Figure 3 gives the scatter band of radial wear for GFRPI-lubricated, plain spherical bearings. The data represent a large number of bearing experiments over a temperature range of room to 315° C at a unit loading of 0.027 GPa (4000 psi), which is a relatively light load for this type of bearing. The bearing will actually accept loads up to about 0.13 GPa (20 000 psi). The radial wear of the GFRPI liner is anywhere from about 13 to 63 micrometers (0.0005 to 0.0025 in.) over 100 000 oscillating cycles of the bearing. These are reasonably low wear rates over a large range of conditions. Another application of GFRPI bearing material is in the bushings or pivots for variable pitch stator vanes (VSV) in the high-pressure stages of advanced compressors. In some of the advanced compressors in jet engines, the gas temperature approaches 370° C (700° F). Very few polymeric materials, other than the most thermally stable of the high-temperature polyimides, can be used at this temperature. In the past certain types of polymeric bushings, which were adequate to about 260° C (500° F), were used. However, GFRPI is serviceable to about 375° C (700° F) at the relatively light loads in the VSV bushing applications. The location of VSV bushings in a jet engine compressor is indicated in figure 4, which the rotating blade array and the compressor housing. The VSV bushings are the pivot points for the stator vanes in the compressor housing. This is a relatively high volume application because there are literally hundreds of VSV bushings in a compressor.

Figure 5 gives the thermal degradation and the wear characteristics of GFRPI bushing materials compared with the material that had been previously used at temperatures to about 260° C. The data were obtained at 357° C (675° F) and 480 kilopascals (70 psi) air pressure. These test conditions simulated the operating conditions in the compressor of an advanced jet engine. The state-of-the-art material degraded severely during 100 hours of static exposure to air at 375° C (700° F). This material lost about 70 percent of its original weight in 100 hours. The data for two types of GFRPI material are shown: one in which the graphite fibers were in the form of a woven fabric, and the other in which the fibers were in the form of chopped fibers. The chopped fibers were as randomly oriented as could be achieved in transfer molding. We can see that the thermal degradation was minimal under these test conditions for both types of polyimide composite. Figure 5 also compares the wear of

COMPOSITE FRICTION COEFFICIENT

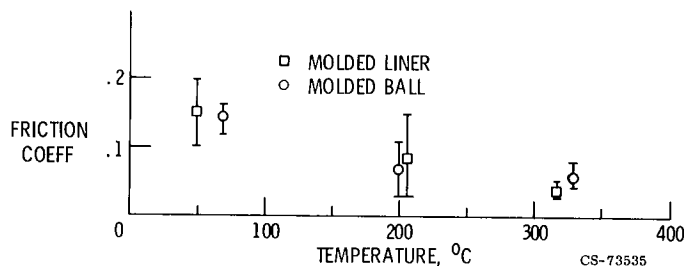


Figure 2

WEAR RANGE FOR GFRPI LINERS

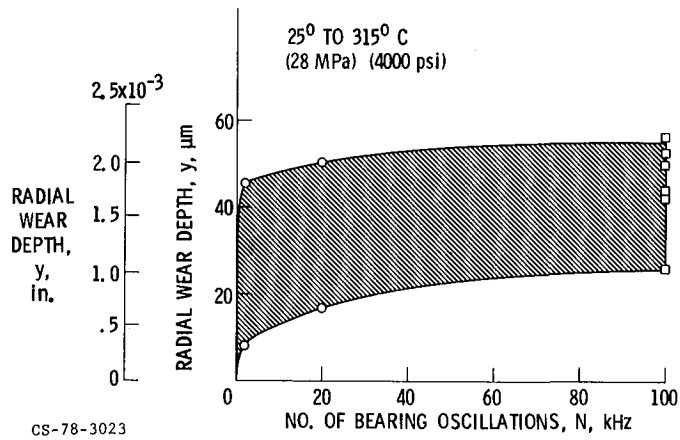
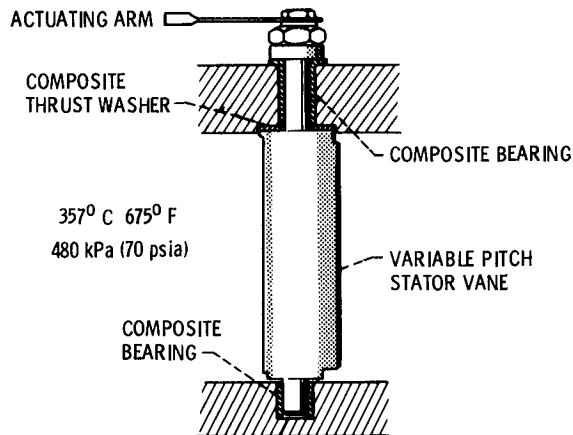
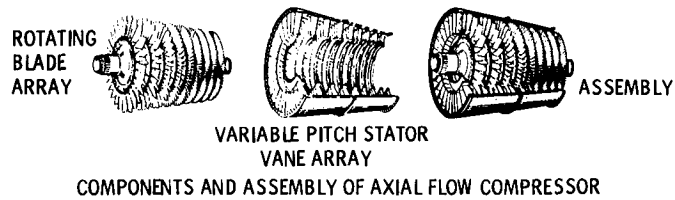


Figure 3

APPLICATION OF POLYIMIDE COMPOSITE IN JET ENGINE COMPRESSORS



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Figure 4

VARIABLE STATOR VANE (VSV) BUSHINGS FOR JET ENGINE COMPRESSORS

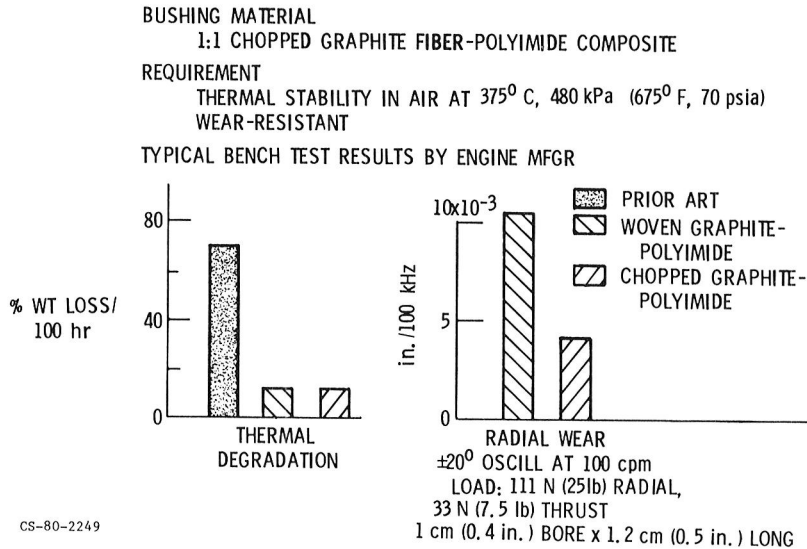


Figure 5

VARIABLE STATOR VANE BUSHINGS FOR JET ENGINE COMPRESSORS

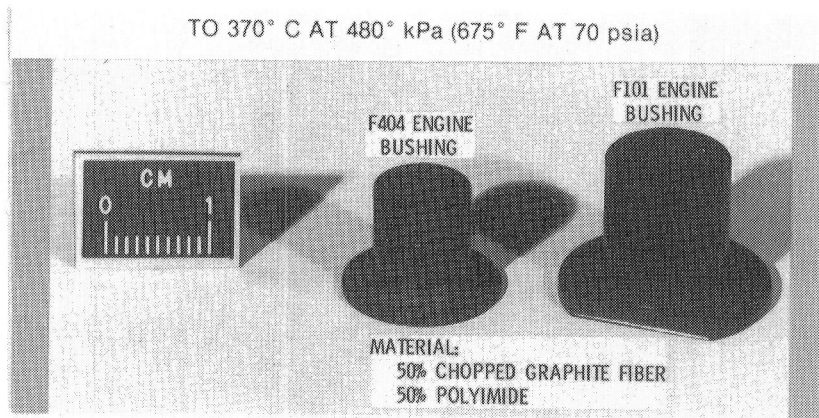


Figure 6

GFRPI with woven graphite-fiber reinforcement with that of GFRPI with randomly dispersed, chopped graphite-fiber reinforcement. The composite with randomly dispersed fiber reinforcement had a considerably lower wear rate. It appears that three-dimensional reinforcement is needed in a bearing; both radial and tangential stresses must be accommodated. Most fabric layups provide reinforcement in two dimensions, but not necessarily in the third dimension which, in the case of a bearing, is usually the radial direction. Therefore, interlamellar shear occurs between the fabric layers, and large, fatigue-type wear particles are formed. A three-dimensional graphite weave may be required to achieve an adequate combination of compressive strength and interlamellar shear strength. With the random chopped fibers, many fibers have orientations with a component in the radial direction. This tends to prevent delamination parallel to the sliding surface.

The photographs of figure 6 show VSV bushings made of chopped fiber GFRPI. They have flanges to carry thrust loads and a cylindrical portion to carry the radial loads. These burhings are now on the bill of materials for two military jet engines.

Inorganic Composites

The components of the inorganic, self-lubricating composites discussed in this presentation are as follows: The metal matrix material is employed to obtain machinability, thermal shock resistance, and a thermal expansion coefficient match with nickel-base superalloys. The thermal expansion match is essential to obtaining adequate bonding when the composites are applied as coatings on nickel-alloy substrates. Hard oxides are sometimes used to improve hardness and wear resistance. Thermally stable fluorides, such as calcium fluoride (CaF_2) and barium fluoride (BaF_2) undergo a brittle to ductile transition at about 540°C (1000°F) and develop a high degree of plasticity (low shear strength) at higher temperatures. This property enables them to function as high-temperature solid lubricants. Finally, glass is added to some composites to function as an oxygen barrier and thereby to provide a degree of oxidation protection to the metal components of the composite.

The inorganic composites can be prepared by any number of powder metallurgy techniques: sintering, hot pressing, etc. One of the convenient ways to prepare them is by the plasma spray coating process shown in figure 7. These coatings are quite thick, typically 0.25 to 0.76 millimeter (0.010 to 0.030 in.) thick. They should not be confused with sputter coatings which are applied by a

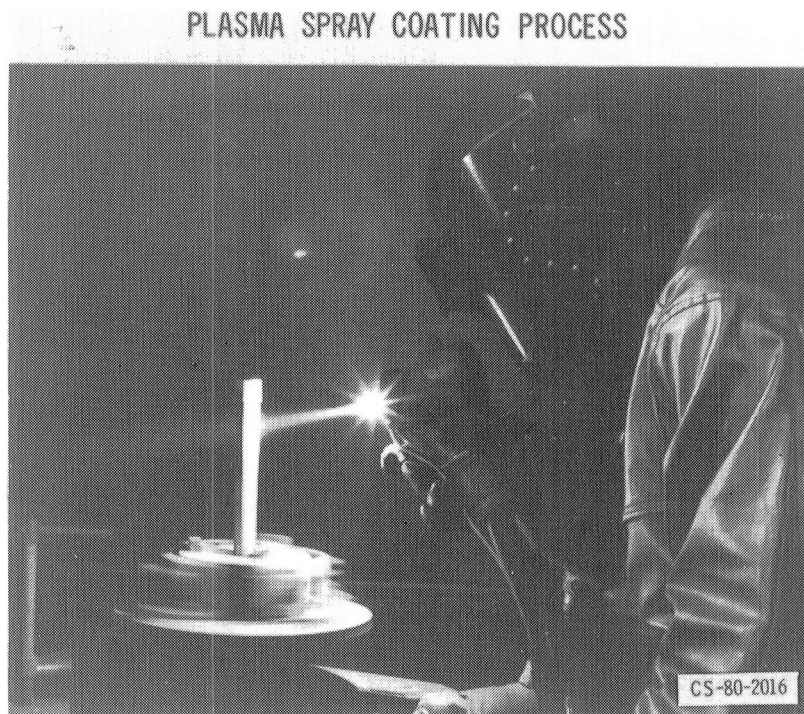


Figure 7

plasma physics process very much different from the plasma spray process. Plasma sprayed, multicomponent coatings are different from most composites in that they are coatings, as opposed to free-standing structures. The plasma spray process consists of transporting powders of the coating components, with a carrier gas through a very high-temperature, high-energy arc that contains ionized gas, usually argon. The particles, in their passage through this plasma of argon, are heated to a very high temperature and melted. They impinge on the material to be coated and adhere by a combination of mechanical and diffusion bonding. An excess coating thickness is applied, then machined back to the desired thickness. This machining operation is not required for some applications of plasma spray coatings, but it is necessary for bearing applications because close

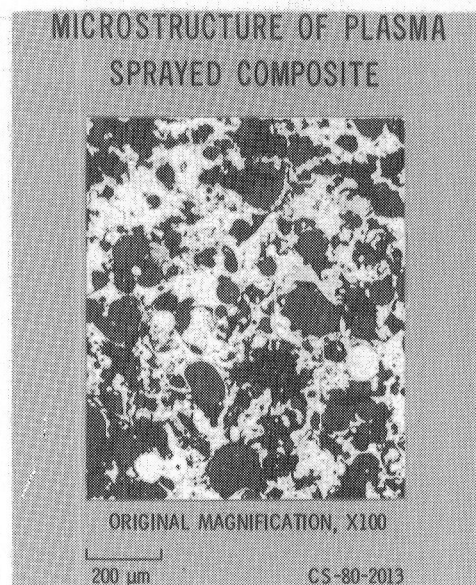


Figure 8

tolerances and a smooth surface finish are required. Figure 8 shows the microstructure of a polished composite coating applied by plasma spraying. It contains a metal alloy (Nichrome), silver, and CaF_2 . The photograph illustrates the uniform distribution of the components in this coating which is self-lubricating over a wide temperature range.

Figure 9 gives the friction coefficient of two composite coatings from room temperature to about 900°C (1650°F). This top curve with the very high friction coefficient is for a plain spherical bearing of a nickel chromium alloy with no coating. (The alloy was, however, preoxidized to reduce the adhesion of the sliding surfaces.) The friction coefficient was quite high over the whole temperature range, and the bearing seized at about 850°C (1560°F). The coating that contains Nichrome, CaF_2 , and glass provided good lubrication from about 500° to 900°C (930° to 1650°F), but it was unsatisfactory at lower temperatures. By the simple expedient of adding silver to the composite, a reasonably low friction was obtained over the entire temperature range and the coating may be considered a wide temperature spectrum, self-lubricating coating.

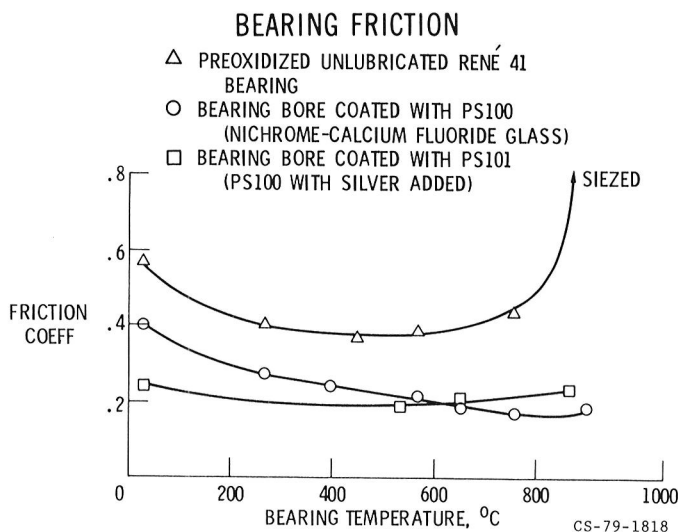


Figure 9

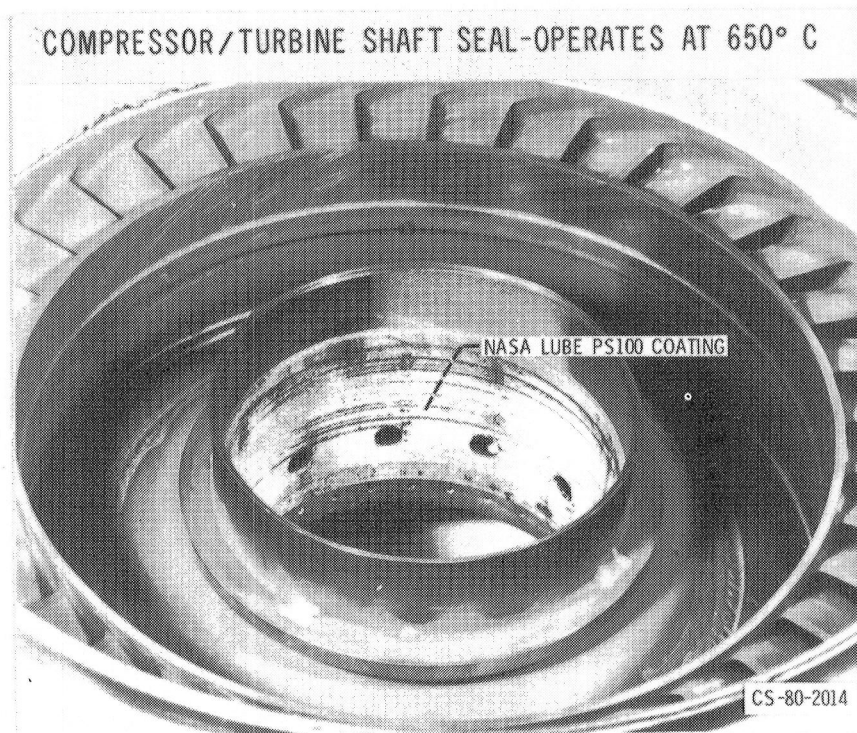


Figure 10

Figure 10 is a photograph of an application for one of these coatings. The coating is the one shown in figure 13, which consists of Nichrome, CaF_2 , and glass. (Silver is not required because low-temperature lubrication is not essential to this application.) In this case the coating is used as an interstage seal material between the compressor and turbine in a small jet engine. The seal operates at 650°C (1200°F). The main shaft of the engine rotates in the seal. The shaft has six knife edges that rub against the coating material. Previously, an abradable porous material was used in this seal, but the erosion rate was very high, and there was considerable gas leakage through the pores of the abradable material. The Nichrome, CaF_2 , and glass were then plasma sprayed as a top coat over the abradable material. Because this coating is nongalling, the knife-edges cut through it cleanly without excessive material transfer. Because the coating is dense, erosion resistance improved, and there was a considerable reduction in gas leakage through the seal.

Summary

To summarize, two classes of composites have been described for use as self-lubricating materials: Polymeric composites, based on polyimide with graphite-fiber reinforcement, are useful to about 350°C (650°F) operating temperature; inorganic plasma sprayed composite coatings are useful to about 900°C (1650°F). Both classes are being used in the aerospace industries and are very promising for application in other industries.

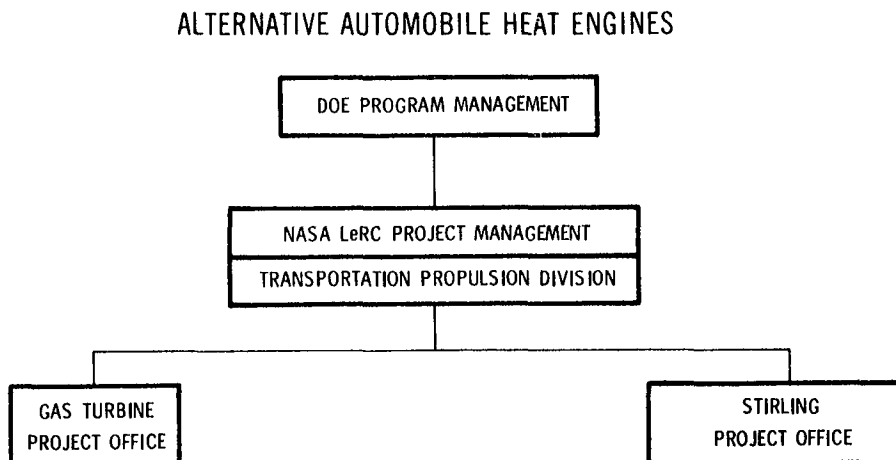
Stirling and Gas Turbine Engines

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Two alternative automobile propulsion systems are the gas turbine engine and the Stirling engine. The Transportation Propulsion Division of the Lewis Research Center has the project management responsibility, under the Department of Energy (DOE), for research and development programs seeking to exploit the potential of these systems (fig. 1). This function is carried out in two project offices.

The potential of these engines includes better fuel economy, the ability to use a wide variety of fuels, including those derived from coal and shale oil, and low emission levels resulting from continuous combustion processes. In addition, they could be competitive in initial cost, and cost of ownership should be lower than that of current spark-ignition or diesel engines.

The projected fuel economy advantage of these alternative engines for the combined metro-highway driving cycle is shown in figure 2. On this plot of fuel economy against inertia test weight, the fuel density is considered to be constant; that is, the higher density of diesel or other fuels does not give engines using these fuels any fuel economy advantage. The lower dashed curve is for current conventional cars; the middle (solid) curve is for current diesels and stratified-charge engines. The upper dashed curve is a projection of what improved diesel and stratified-charge engines might do. The 1985 corporate average fleet economy (CAFE) standard of 27.5 mpg is also shown, together with the estimated fuel economy for the alternative systems in a 3100-pound car. These systems achieve 36 mpg, considerably better than the CAFE standard and significantly better than that achieved by the improved diesel and stratified-charge engines. The estimated upper weight limit for diesel-powered automobiles resulting from current planned particulate emission levels is approximately 2600 pounds.



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Figure 1

METRO-HIGHWAY FUEL ECONOMY VS INERTIA WEIGHT

CONSTANT FUEL DENSITY

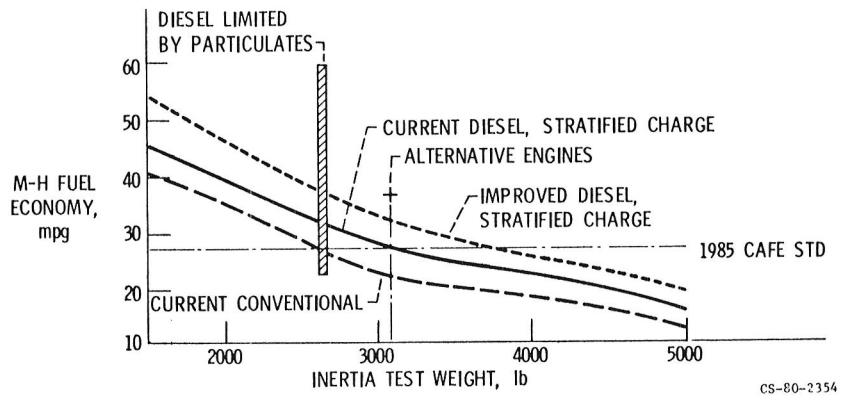


Figure 2

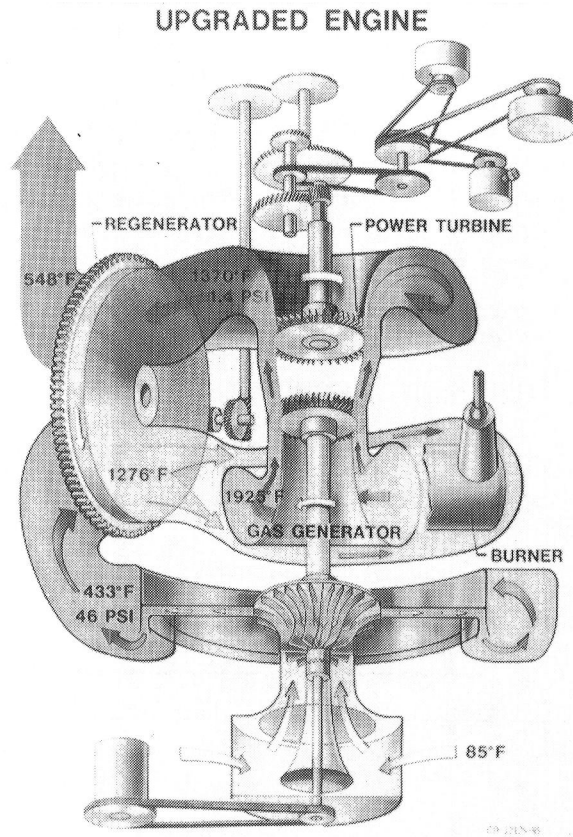


Figure 3

The current state of the art for automotive gas turbines is represented by the Chrysler/DOE experimental upgraded engine. A schematic of this engine, presented in figure 3, shows some of the features of an automobile gas turbine. It is a close cousin to the aircraft turboprop but is about one-quarter the size of the smallest of these. Its principal difference is the incorporation of a heat exchanger, called a regenerator, to put waste heat back into the system in order to improve efficiency. Air that has entered the engine and been compressed enters the regenerator, where it picks up heat from the exhaust gas to increase its temperature before it enters the combustor. The hot, high-pressure products of combustion drive the turbines. One turbine is on the same shaft as the compressor and drives it. The other turbine drives the car wheels through a transmission. (In another version, one turbine drives both the compressor and the wheels.) The gas leaving the turbine passes through the regenerator to give up some of its heat before it enters the exhaust system.

Although the gas turbine looks quite different from conventional automobile engines, the Stirling engine does have some components in common with them. A cutaway of a 55-hp engine designed as a laboratory engine for development work by United Stirling of Sweden is shown in figure 4. It does have pistons, connecting rods, and crankshafts, but in its operation it is more like a reciprocating steam engine. It too has a closed-system working fluid, in this case hydrogen or perhaps helium, which is heated by products of combustion generated in an external combustor as they pass over heat-exchanger tubes. In the Stirling, the working fluid is always gaseous, and it is shuttled back and forth between the hot end of the engine and the cold end by the pistons, which serve this additional

55-HP STIRLING ENGINE

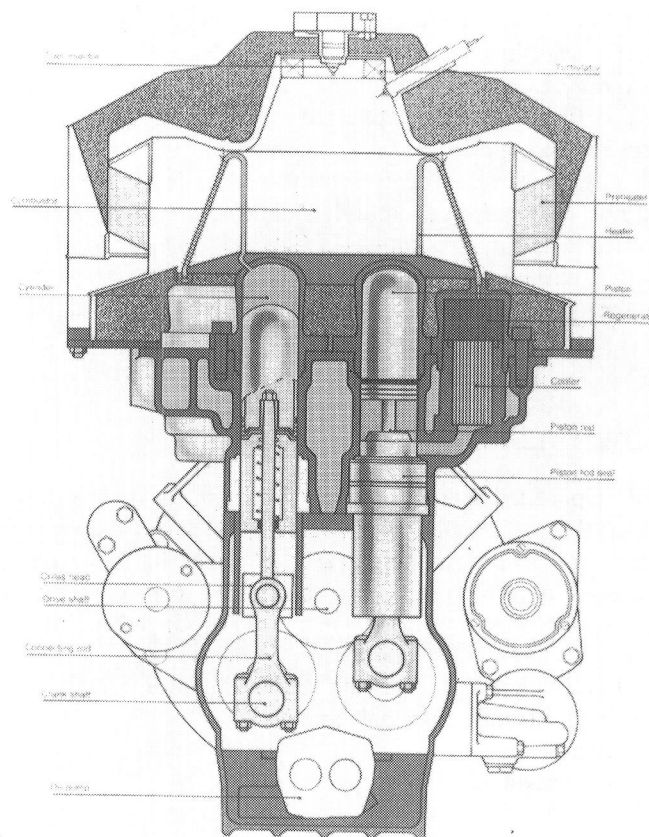


Figure 4

TABLE I.—MAJOR HEAT ENGINE CONTRACTS

[Completion by May 1985.]

Contract	Date	Cost, dollars
Advanced Stirling engine development MTI/USS/AMG	3/78	90×10^6
Advanced gas turbine development AiResearch/Ford	10/79	57×10^6
DDA/Pontiac	10/79	65×10^6
Ceramic applications in turbine engines (completion, mid-1984) DDA	1/78	43×10^6

function. After driving the piston the hot expanded gas deposits much of its heat to a regenerator as it is moved to the cold end, where it is cooled further and compressed. On its way back to the hot end it picks up the heat previously deposited in the regenerator. The Stirling engine uses a lot of heat exchangers.

The NASA Lewis Research Center has three major contracts at this time to develop technology for, and experimental versions of, alternative automobile engines (table I). All the contracts are cost sharing in some form and of several years duration. The dollar values shown in the figure give some idea of the resources being brought to bear on alternative engine work. The Stirling engine development contract team is headed by Mechanical Technology Incorporated of Latham, New York, and includes United Stirling of Sweden and American Motors General. The two gas turbine teams are AiResearch (prime) with Ford and Detroit Diesel Allison (prime) with the Pontiac Division of General Motors. One additional major contract is listed in table I. Detroit Diesel Allison is conducting a program on ceramic applications in turbine engines, in which they use their heavy-duty truck/bus gas turbine as an R&D engine. This effort was designed to form the cutting edge of ceramic technology for automobile engines.

The three major engine development contracts are designed to develop and demonstrate technology to the point where the automobile manufacturers can make a decision about a first commitment to commercialization. As shown in figure 5 the Government-sponsored program could be followed by industry activities moving down the commercialization path to mass production by the early 1990's. But these development programs carry high risks, and that is why the Government is supporting them.

The Gas Turbine Engine

The Chrysler/DOE Upgraded Engine was designed primarily for low emissions performance. Installed in several Chrysler cars, including the restyled LeBaron shown in figure 6, its fuel economy is no better than that of a conventional engine. To improve the fuel economy of an automobile gas turbine to the 36-mpg level in a 3100-pound car, the turbine inlet temperature must be raised to 2300° to 2500° F. The only reasonable way to do this in a mass-produced engine is to use ceramics in the hot components.

Existing ceramics already have the following required characteristics:

- (1) Low-cost raw material (sand, charcoal, and air)
- (2) Excellent wear resistance
- (3) Excellent corrosion resistance
- (4) Light weight
- (5) Low thermal conductivity

In our programs we are striving to obtain ceramic components that can be formed very close to final shape in order to minimize expensive grinding operations and thus lower the cost. These components

AUTOMOTIVE HEAT ENGINE COMMERCIALIZATION

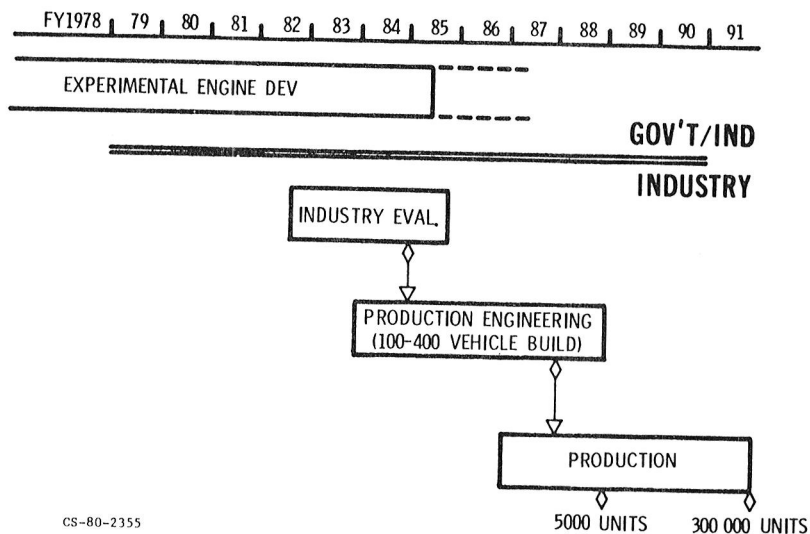


Figure 5

CHRYSLER LEBARON WITH UPGRADED ENGINE

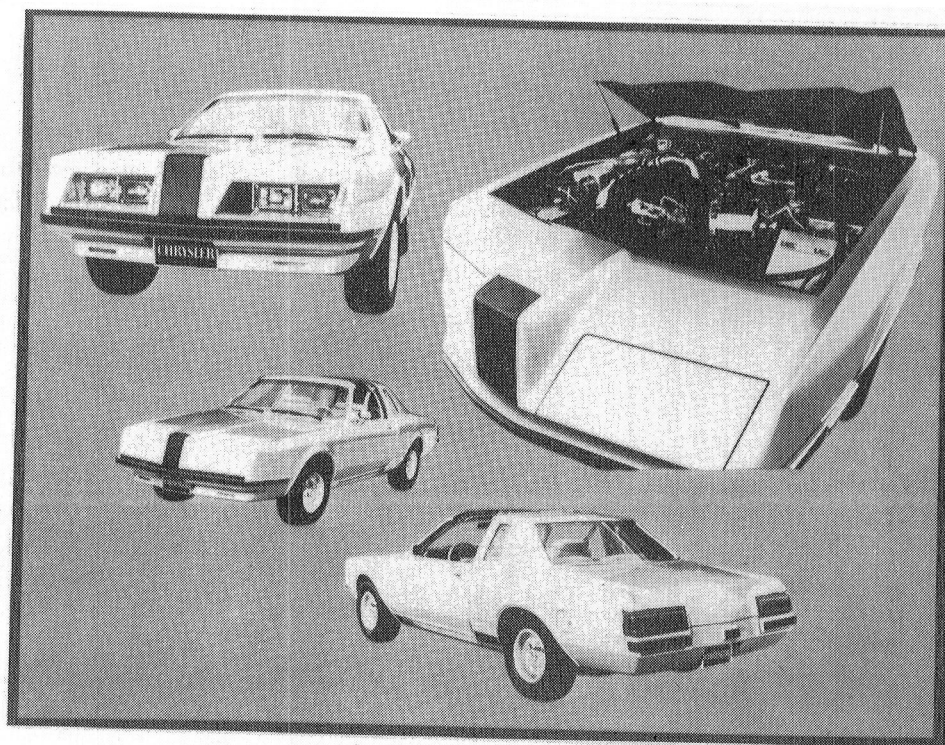


Figure 6

must be able to withstand the thermal shocks to which they will be exposed in automobile driving cycles. And they must have high strengths for use in the most difficult component, the turbine rotor. Our goal for ceramics for this use is a characteristic bend strength of at least 80 ksi in 999 of every 1000 test specimens.

Many ceramic material suppliers and fabricators are involved in our projects. A list is shown in table II. Most of the effort now is on the structural ceramic materials, SiC and Si₃N₄. The Corning aluminum silicate material or its improved derivatives have already demonstrated significant capability for our regenerator needs. Some of these manufacturers have products made of these materials on the market, for example, papercutter bars, pump mechanical seal rings, industrial process heat exchangers, improved spark plug insulators, improved electrical insulators, and insulation anchors for high-temperature furnaces. Others are developing products they hope to market, such as an automobile engine valve lifter, diesel preignition chambers, a diesel piston head cap, and a turbocharger rotor. The SiC turbocharger rotor being developed for production is shown in figure 7. An SiC plenum—a rather large, complex shape—being made for our ceramic applications program is shown in figure 8. Long-wearing ceramic pump seal rings like those shown in figure 9 are being produced in very large quantities and are commercially available.

The basic configuration of the automotive ceramic heat exchanger has been improved to yield higher effectiveness (fig. 10). The honeycomb wall thickness of the original aluminum silicate has been reduced by Corning from 55 to 35 mils to achieve this. They are now working on producing the lower thickness in a higher temperature material. This basic honeycomb has been fabricated into very large regenerators for industrial applications, as shown in figure 11. A schematic of such an application, designed to reduce fuel costs by recovering waste heat, is shown in figure 12. The large rotating regenerator passes through the hot furnace exhaust and then through the air entering the combustor. As fuel costs increase, the cost of retrofitting engines with such a system becomes increasingly attractive.

As a result of Lewis' efforts to solve the problems associated with the very high turbine inlet temperatures required for an automobile gas turbine, it is likely that a new class of materials may be made available that are attractive in a great many applications.

The Stirling Engine

The mechanical-drive 55-hp Stirling engine, shown in cutaway in figure 5, has been installed in two different cars even though it was not optimized for an automobile duty cycle. The complete powertrain except for differential and radiator is shown in figure 13. In an AMG Spirit, figure 14, it displayed fuel economy about equal to a conventional engine and low emissions. It uses hydrogen as its working fluid.

TABLE II.—CERAMIC MATERIAL

MANUFACTURERS

	Type of Material
Carborundum	SiC
GTE Sylvania	Si ₃ N ₄
AiResearch	Si ₃ N ₄
Norton	SiC and Si ₃ N ₄
Pure Carbon/British Nuclear Fuels	SiC
Annawerk (W. Germany)	SiC
Rosenthal (W. Germany)	SiC and Si ₃ N ₄
Kyocera (Japan)	SiC
Toshiba (Japan)	Si ₃ N ₄
Corning	AlSi

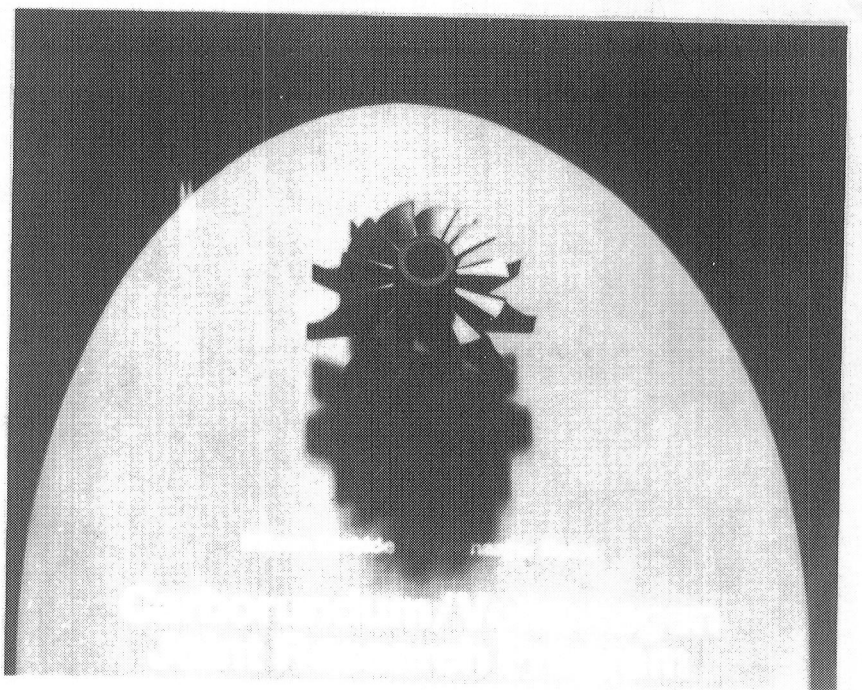


Figure 7



Figure 8

CERAMIC PUMP SEAL RINGS

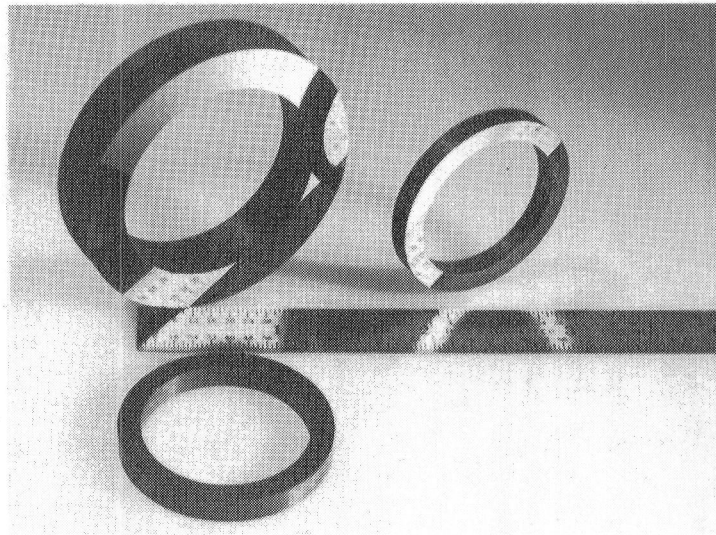


Figure 9

CERAMIC REGENERATOR DEVELOPMENT

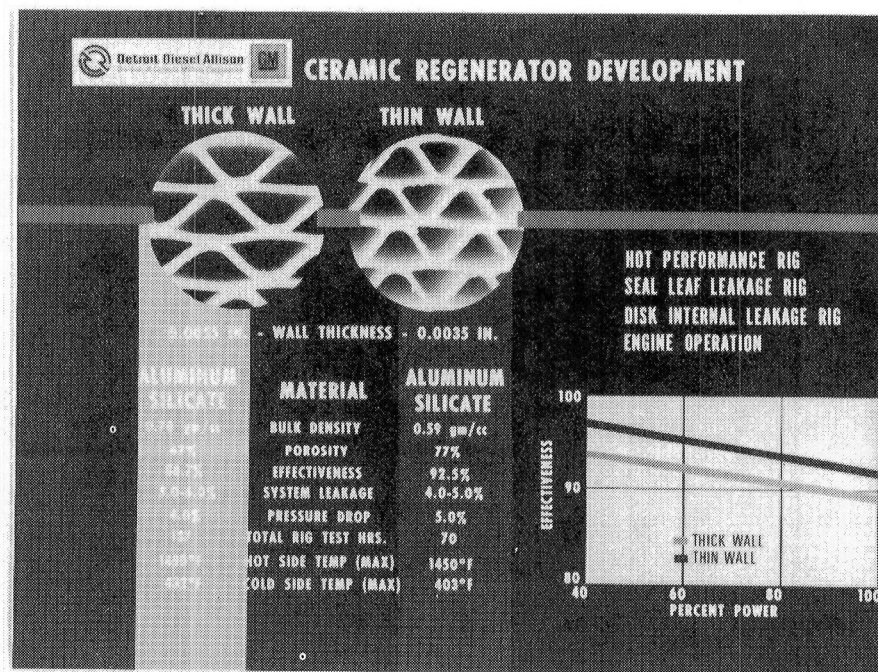


Figure 10

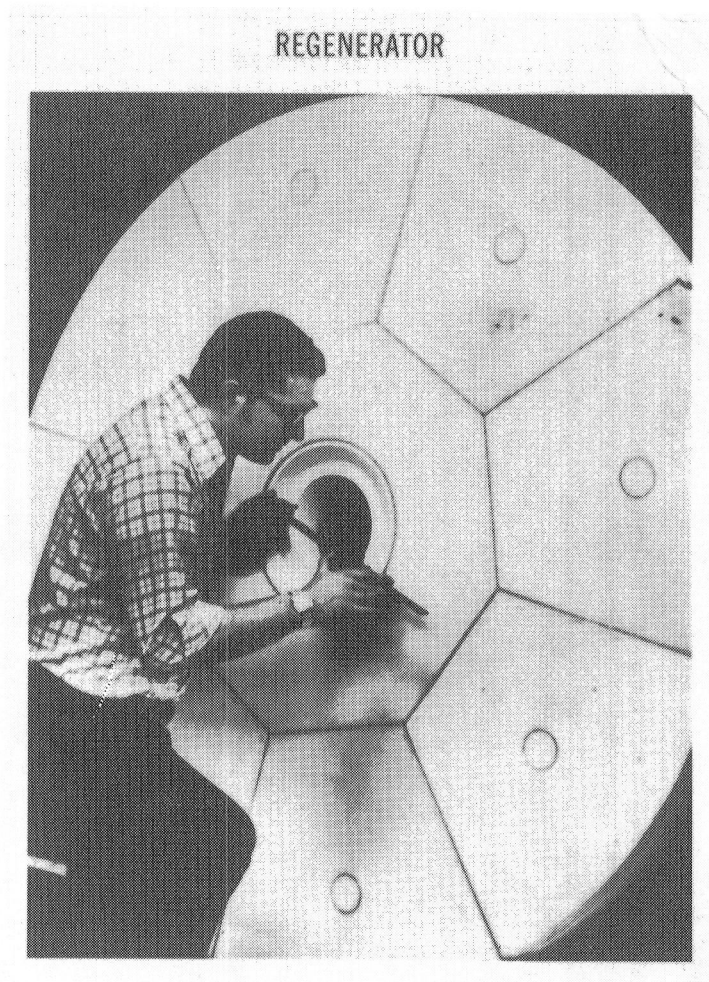


Figure 11

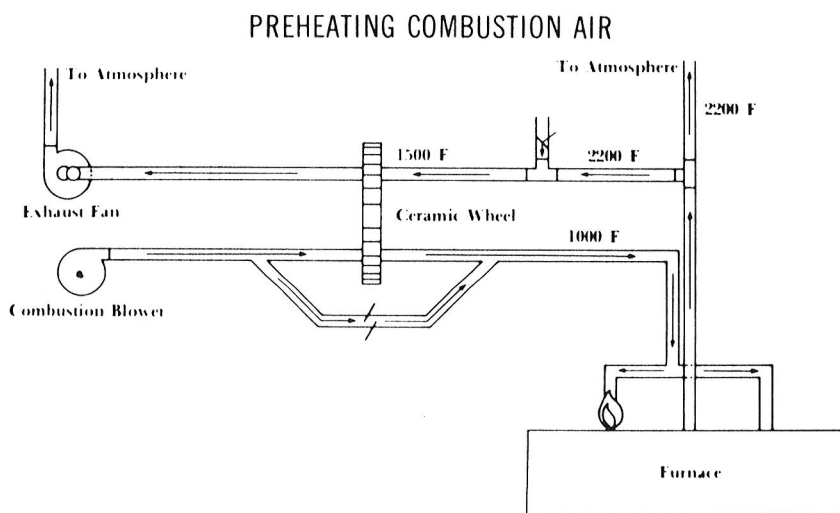
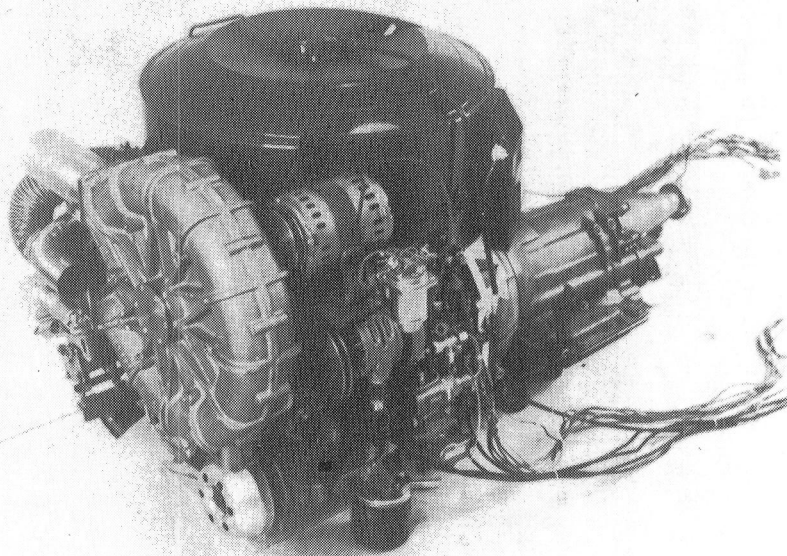


Figure 12

STIRLING ENGINE POWERTRAIN



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Figure 13



STIRLING-POWERED 1979 AMC SPIRIT

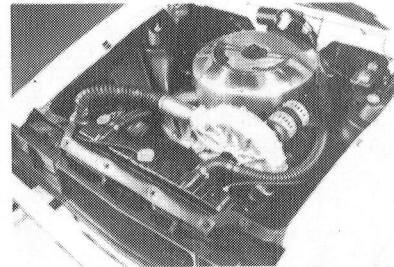


Figure 14

There is another type of Stirling engine, the free-piston engine, that does not require the heavy mechanical components of the mechanical-drive Stirling engine. In this case the pistons are directly connected to a device that uses reciprocating motion to produce power output, such as a linear alternator or a pump. In this way several advantages can be realized. Dynamic seals and the mechanism required to convert reciprocating to rotary motion can be eliminated, simplifying the engine and increasing reliability. The system efficiency can be higher, and since the control of the engine is inherent in its internal design, no external pressure or volume control system is required. The small free-piston engine shown is being characterized in our laboratories.

Both the free-piston and mechanical-drive Stirling engines have a unique multifuel capability. Not only can they use a wide variety of liquid fuels and gases like the gas turbine, but they can also burn powdered coal. In addition, they can work directly from thermal energy like solar heat and from stored heat sources.

People are using, or exploring the use of, the unique characteristics of this engine. A Stirling engine auxiliary power unit for recreational vehicles (fig. 15) is scheduled to be on the market early next year. Lewis is studying analytically and experimentally, for the Bureau of Mines, the possibilities of using Stirling engines in mining applications (fig. 16). An active solar thermal application project is being funded by DOE. In this case solar collectors focus the Sun's energy into a receiver, through which the working fluid passes to pick up heat (fig. 17). Several companies are working on Stirling heat pumps, some of them being free-piston pumps (fig. 18).

The key development problems requiring additional work in the Stirling engine include methods for increasing operating temperatures and thereby efficiency: high-temperature heater tubes; efficient, low-cost heat exchangers (regenerators and coolers); durable, low-friction seals; efficient control schemes; and durable, low-cost engine designs. For some applications adequate technology already exists to obtain the Stirling engine's advantages: multifuel capability, high thermal efficiency, very low emissions, and a very quiet energy conversion system.

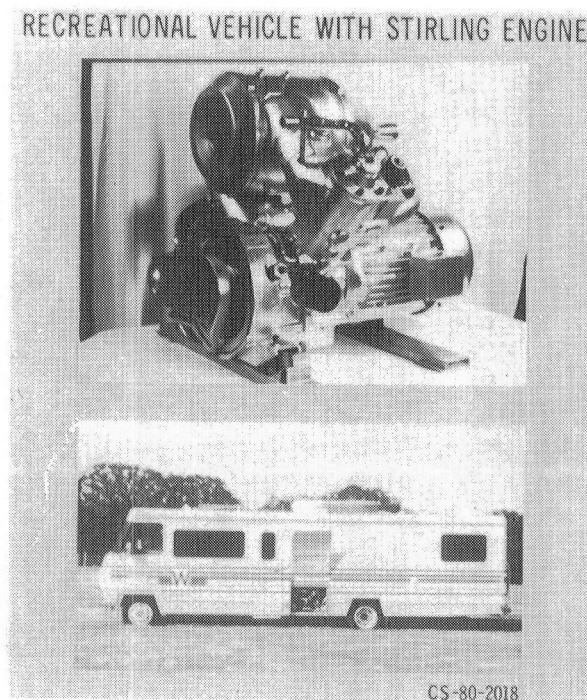


Figure 15

MINING APPLICATION FOR STIRLING ENGINE

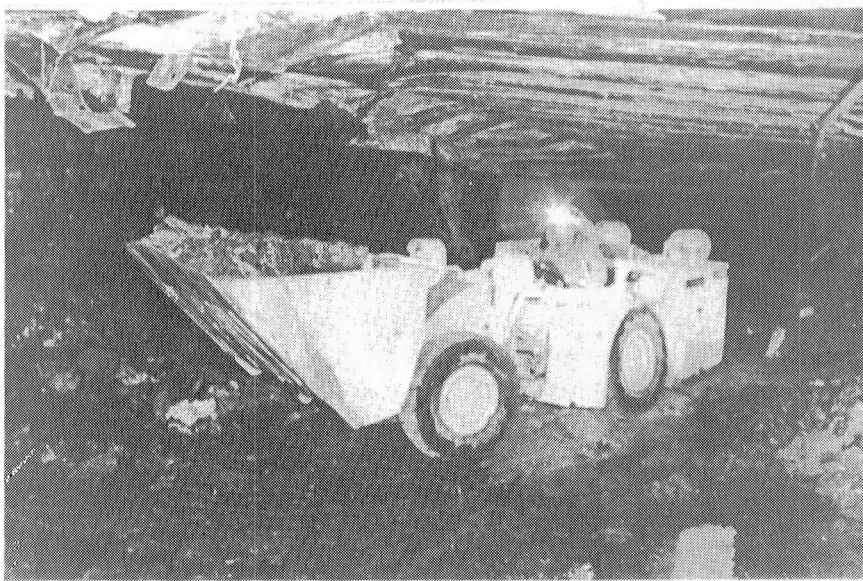


Figure 16

LOW-COST HEAT-PIPE SOLAR RECEIVER/TES/STIRLING ENGINE-GENERATOR

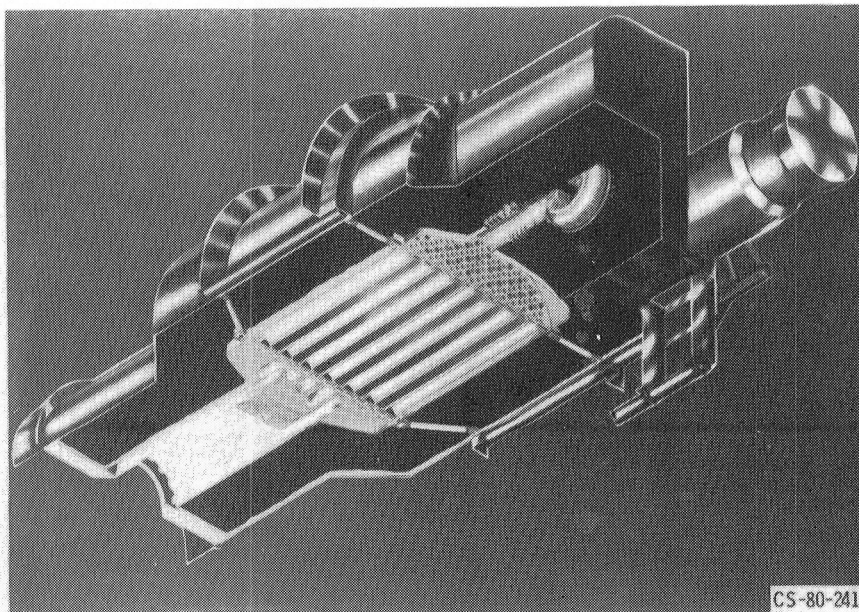
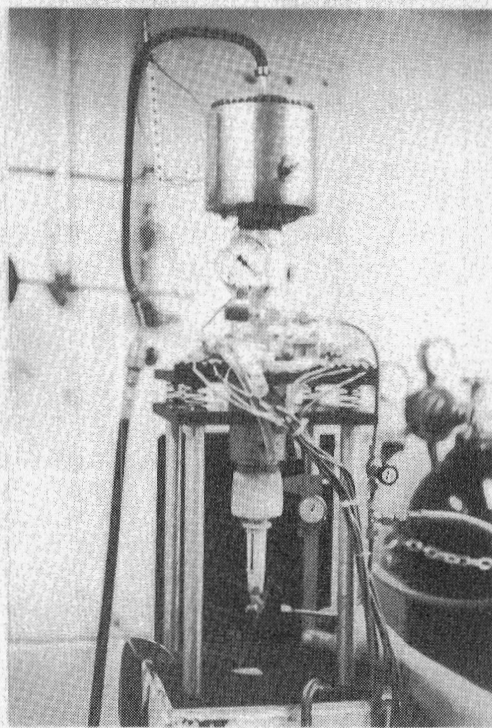


Figure 17

FREE PISTON HEAT PUMP



CS-80-2011

Figure 18

Propulsion System Research and Development for Electric and Hybrid Vehicles

Harvey J. Schwartz

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The NASA Lewis Research Center is responsible for planning and implementing all propulsion system research and development work being supported under the Department of Energy's Electric and Hybrid Vehicle program. During the past 3 years the propulsion system project has grown until it now involves participation by approximately 30 industrial firms and universities through contracts and grants totaling over \$7 million.

Present-day propulsion components and systems are unsuitable for a mass-produced consumer electric vehicle for two reasons. One is that available components are not designed for road service. As a result they are heavy and expensive and have relatively low efficiencies. In many cases basic performance data taken under conditions that are encountered in electric vehicle service are not available. The second reason is that the market for electric vehicles is not large enough, nor does it appear to be near-term enough, for manufacturers to invest funds in developing custom-built components for electric vehicles. Not only do the component manufacturers lack incentive to produce new products on their own, but the electric vehicle manufacturers do not have enough leverage with their suppliers to get the necessary technology development done. Therefore propulsion component and system technology development must be Government-supported for at least the near future in order to stimulate electric and hybrid vehicle commercialization.

The Lewis Research Center's approach to propulsion subsystem technology is as follows: For the next few years we will be providing engineering information to manufacturers that will assist them in building better electric vehicles. This will be done primarily through testing components now available to manufacturers and publishing data on their performance and through developing a component catalog that will give manufacturers a source of information on where to obtain propulsion components for their vehicles. Technology development in the near term will involve the development of improved components and propulsion subsystems based on existing technology. The philosophy here is to adapt the best existing techniques and designs to produce components specifically for electric and hybrid vehicle use. In the long term, advanced components and systems will be based on totally new technologies and will be quite different from those on the market today. The emphasis in all the development work is on cost, weight, and efficiency, with cost being the primary factor at present. This is because our studies show that if large-scale production of an electric vehicle were to take place using existing propulsion technology, as much as 50 percent of the cost of the vehicle to the consumer would be associated with the propulsion system. Therefore propulsion R&D offers a great opportunity for reducing the cost of electric and hybrid vehicles.

Component Characterization

Component characterization work is designed to provide engineering data to manufacturers on component performance and on important component-propulsion system interactions. Work is under way on motor and controller testing, transmission testing, and the study of battery-propulsion

system interactions (fig. 1). The Eaton Corp. is the major contractor for motor, controller, and transmission testing and TRW, Inc., is conducting a battery testing project. Examples of the results of this work are shown in figures 2 and 3.

In figure 2 the efficiency in percent is plotted against the output in kilowatts for an electric vehicle traction motor operated in two different manners. The upper curve shows its performance on ripple-free dc electricity; the lower curve shows the way the motor performs when it is coupled with a conventional chopper type of dc motor controller. The ripple-free dc characteristic curve is typical of what an electric vehicle manufacturer obtained from a motor supplier's catalog; the chopped dc curve represents how the motor actually operates with a typical speed controller that would be used in a vehicle. Notice that in some areas, particularly at low power outputs, the difference between the two curves can be as much as 10 percentage points. This difference in efficiency results in a direct reduction of the range of the vehicle.

Figure 3 shows the performance of a three-speed automatic transmission from a compact car. Here the efficiency is plotted against the output speed under a range of conditions that are typical of what the transmission would see if it were operating in an electric vehicle. In an ordinary passenger car this transmission would have an efficiency approaching 90 percent, but in an electric vehicle it is operating sufficiently far from its optimum design point that the efficiency reaches a maximum of only about 80 percent. Again this results in a significant drop in range. Thus it is clearly important for the vehicle manufacturers to have performance data of this type. Unfortunately, this kind of data is not normally available from the component suppliers, and the vehicle manufacturer usually does not have the resources to provide it for himself.

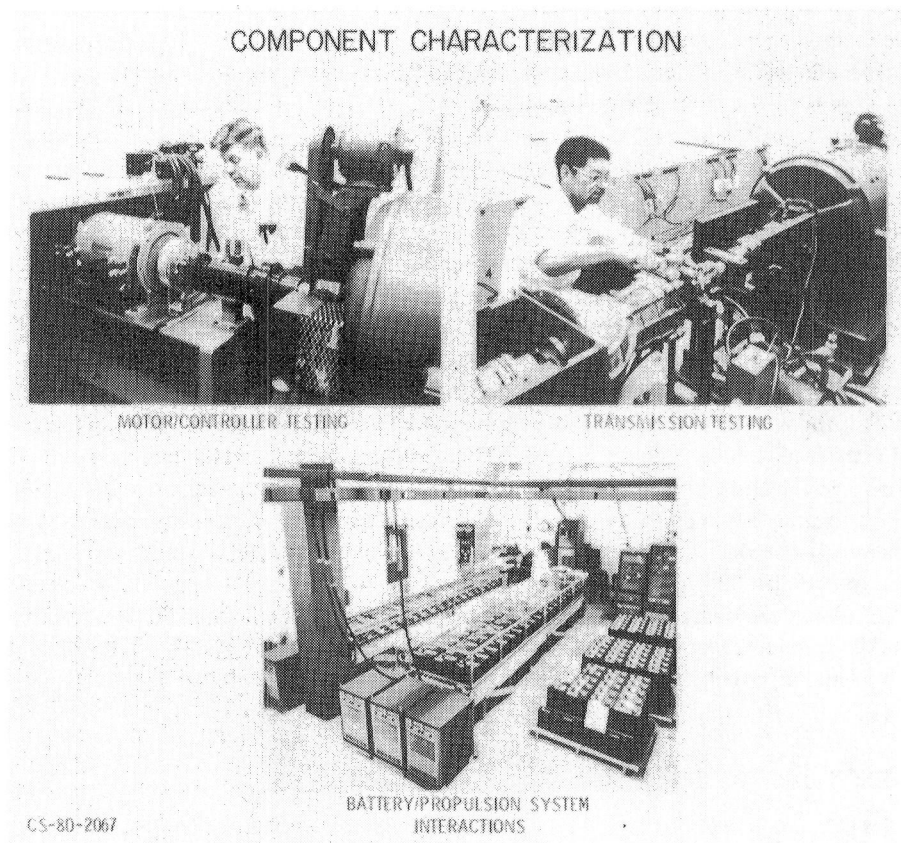


Figure 1

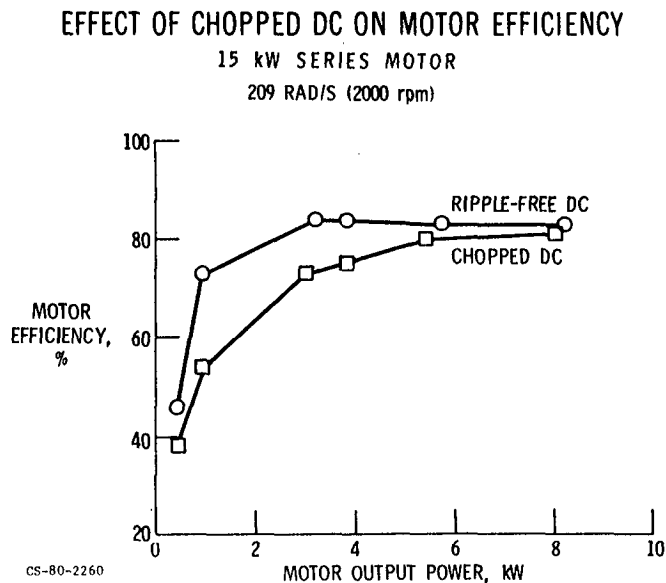


Figure 2

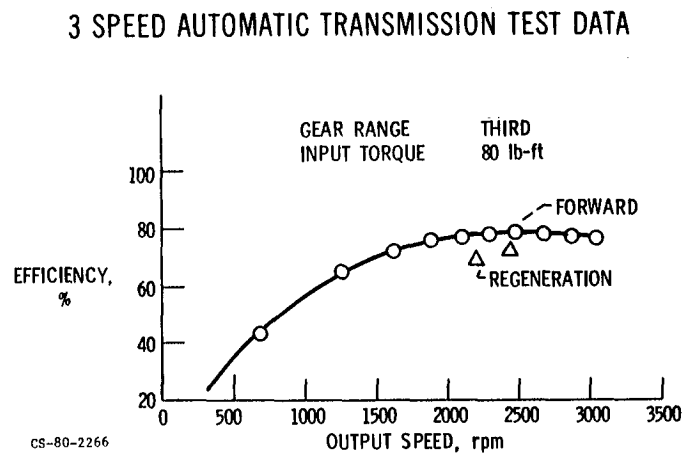


Figure 3

Component Development

The NASA Lewis technology development program is focused on three separate areas: One is power conditioning, which relates to the development of motor controllers. The second is the development of new traction motors of various types. The third involves transmissions designed specifically for electric and hybrid vehicles. Our long-term goal is to provide a propulsion system that has an efficiency approaching 80 percent under urban driving conditions and that will cost approximately \$80 per kilowatt of rated power output and weigh about 7 kilograms per rated kilowatt. If we can reach these goals, the long-term effect would be a 20- to 30-percent reduction in the sticker price of an electric car and a 15- to 20-percent reduction in the overall life-cycle cost of that car to its owner.

Examples of our work on traction motor development are shown in figure 4. The improved motors that are being developed by AiResearch Manufacturing Co. and Virginia Polytechnic Institute use existing technology and are rather conventional in appearance and design. The advanced motors shown in the lower part of the figure are radically different. They emphasize the use of low-cost materials and novel design approaches that can result in smaller, lighter, and cheaper motors. The contractors for our advanced motor work are the General Electric Co., Westinghouse, and the Garrett Corporation's AiResearch Manufacturing Co. Other propulsion components presently under development are shown in figure 5. Motor controllers are being developed by the Chrysler Corp., General Electric, and Gould. The left photograph in the upper part of the figure shows a high-frequency (10-kHz) chopper type of controller that has been built and tested by Chrysler. It has an efficiency in excess of 90 percent over most of its operating range. The high frequency has a side benefit in that it tends to eliminate the characteristic unpleasant whine associated with the lower frequency choppers now used in controllers for electric vehicle motors. The right photograph shows a "breadboard" version of a motor controller being developed by General Electric that uses a new, lost-cost power transistor also under development at GE.

Continuously variable transmissions could be of great value not only to electric vehicles but to conventional automobiles as well, since they provide a way of improving the match between the motor output and the road load. Several promising designs are being investigated for electric and hybrid vehicle use, but it will be a number of years before they are available for installation in vehicles because of the difficult engineering problems that must be solved.

Propulsion System Development

NASA Lewis is also supporting the development of complete propulsion systems, for example, the ac drive being developed for Lewis by the Eaton Corp. (fig. 6). It consists of two major parts: One is

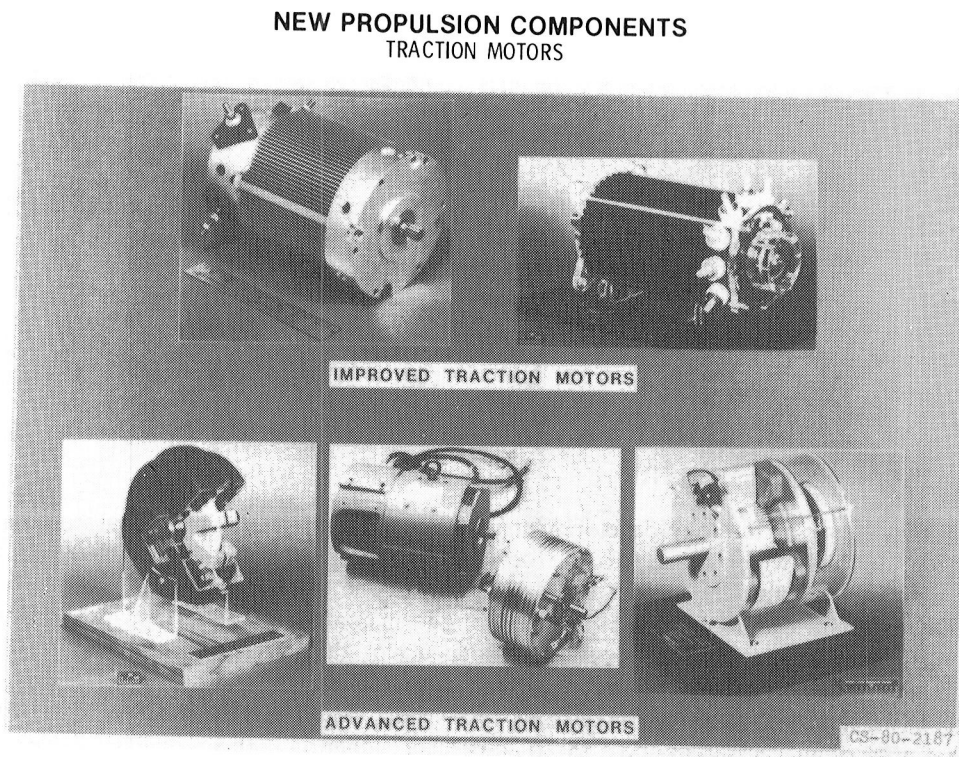


Figure 4

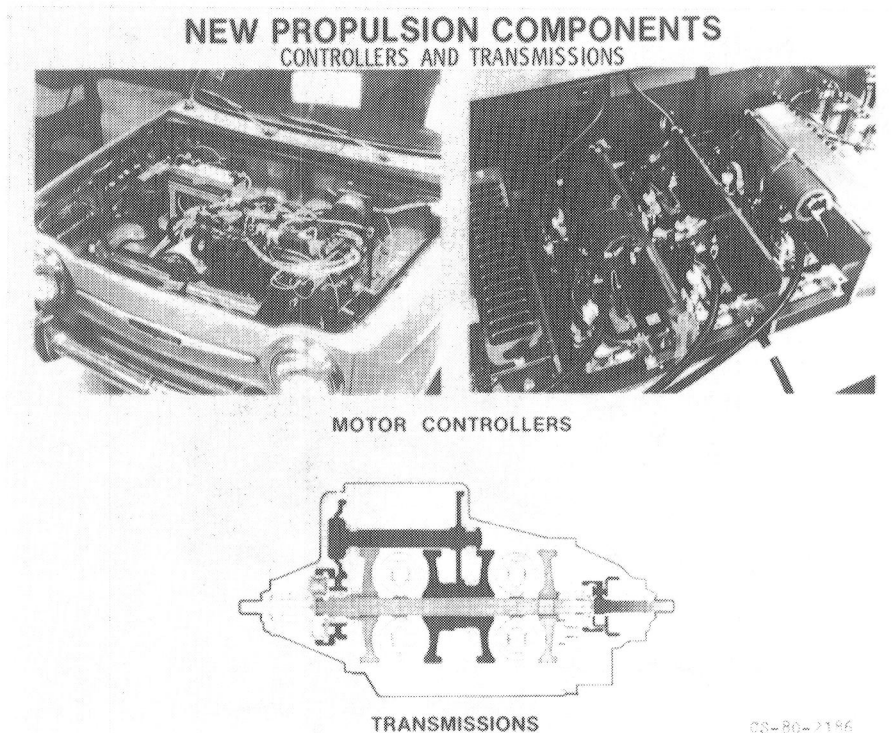


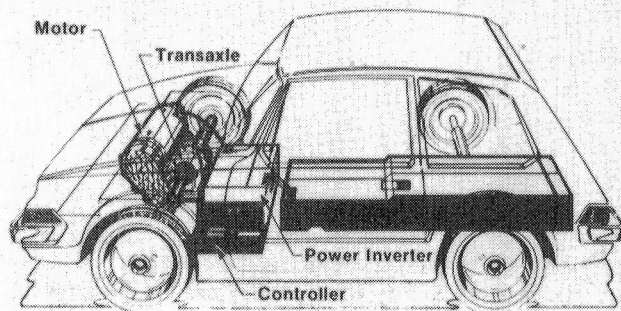
Figure 5

the ac motor, its controller, and a microprocessor or computer that controls the motor. The other is a two-speed, geared, automatic transaxle. The advantages of ac drives are well known. The motors are small and lightweight, require little maintenance, and lend themselves to mass production at low cost. The main disadvantage to an ac drive at present is the cost of the power transistors required for the inverter that controls the motor. The transaxle has been tested and has an efficiency of greater than 90 percent. An attractive feature of the transaxle is that it can also be used with a dc drive if it turns out that the transistor cost reductions do not come about as rapidly as they are expected to. The lower sketch in figure 6 shows an artist's conception of how the system would look if installed in a subcompact car of the Ford Fiesta size.

Propulsion system testing is expensive and difficult if it is done in a complete vehicle. This summer the Lewis Research Center will dedicate a new facility called the Road Load Simulator Facility. This unique laboratory is designed for testing electric and hybrid vehicle propulsion systems over a wide range of driving conditions in a variety of simulated vehicles at low cost and with high accuracy and reproducibility. We will be able to test propulsion subsystems under the conditions they would see in many kinds of vehicles, ranging from small subcompact cars to large delivery vans. A programmable driving-schedule controller will allow us to reproduce almost any type of traffic condition. The result will be accurate, convenient, cost-effective testing of electric and hybrid propulsion systems. The first system to be tested is shown in the lower right of the figure. It is the propulsion subsystem from the General Electric-Chrysler ETV-1 electric vehicle, which was developed for the Department of Energy and is described in the paper by Thomas Barber of the Jet Propulsion Laboratory.

In summary, the NASA Lewis Research Center expects four major benefits to accrue from our propulsion system R&D work. First, we will provide current vehicle manufacturers with engineering design data and new propulsion components and systems that will assist them in producing better vehicles. Second, we will improve the technology base from which vehicle manufacturers can draw in the future in designing commercial vehicles. Third, we expect to help reduce the near-term R&D

PROPULSION SYSTEM DEVELOPMENT



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Figure 6

investment required by industry while the potential market is uncertain. And finally, we expect to significantly reduce the purchase price and ownership cost of mass-produced electric and hybrid vehicles.

Since we are dealing in research and development work that is associated fairly closely with a potential commercial product and are attempting to stimulate an earlier commercialization of that product, we believe that new approaches are going to be required in our R&D contracts. We feel that it will be necessary to provide incentives to industry in the form of cost and risk sharing at times when market conditions make R&D investment by industry on their own unlikely. These incentives might take the form of exclusivity in data and patent rights in return for which we would expect industry to pay back the Government's investment if the projects are successful. This is something that is already being done in our aeronautics program. Furthermore we will have to protect the taxpayers' interests by insisting on "march in" rights to have others continue the work if the company decides to drop the project and a market still appears to exist. We are presently discussing an approach to this type of procurement activity with the Department of Energy for possible use in future procurements.

Concluding Remarks

The electric vehicle was once a major factor in our Nation's transportation system. Today we are seeing rebirth of the electric vehicle industry based on conversions of conventional automobiles and light trucks and a few purpose-built electric vehicles with somewhat limited performance. By the mid-1980's, however, we expect this industry to grow to the point where mass-produced, carefully engineered electric vehicles with high consumer appeal are going to begin to appear on the roads.

The Federal Electric and Hybrid Vehicle Program

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On September 17, 1976, the Congress passed Public Law 94-413, which created a Federal program of research, development, and demonstrations to promote the commercial development and use of electric and hybrid vehicles. The law placed the responsibility for the program with the Department of Energy (DOE).

As illustrated in figure 1, electric and hybrid vehicles are of importance today because they represent one way in which we can move our Nation's transportation system off a petroleum energy base and onto an energy base that would consist of whatever form of energy the local electric power company was using. Obviously, that could mean the use of coal, nuclear power, or any of the other sources shown in the figure to fuel our automobiles. Within the DOE program, an electric vehicle is defined as one that is fueled solely by wall-plug electricity. A hybrid vehicle is one that uses a combi-

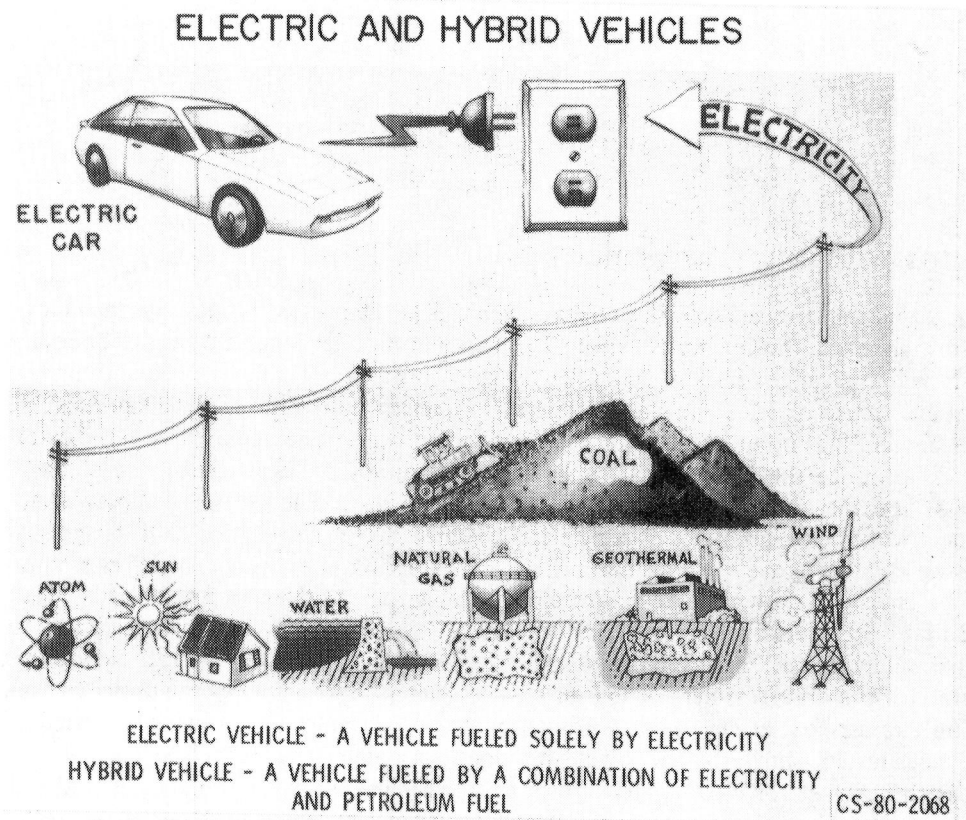


Figure 1

nation of wall-plug electricity and a petroleum fuel. The organization of the DOE Electric and Hybrid Vehicle program is shown in figure 2. The program is divided into five separate projects. The Vehicle Evaluation and Improvement project has as its goals the development of a 50-mile-range delivery van and the general upgrading of existing vehicle technology by 1986. The goal of the Electric Vehicle Commercialization project is to have in place in private industry the manufacturing capability to produce a 100-mile-range electric passenger car, also by 1986. The Hybrid Vehicle Commercialization project has established a goal of producing a commercially viable hybrid vehicle with a range comparable to that of a conventional automobile by 1988. The Advanced Vehicle Development project is targeted for 1990. Its goal is to develop a vehicle that has all the performance and range capability of present-day vehicles but is independent of petroleum as a fuel. This could mean either electric vehicles running on electricity generated from other fuels or hybrid vehicles that use synthetic fuels derived from nonpetroleum sources. In support of these four projects there is an on-going Market Demonstration project that seeks to place 10 000 electric and hybrid vehicles into public and private sector demonstrations within the next 4 years.

FEDERAL ELECTRIC AND HYBRID VEHICLE PROGRAM

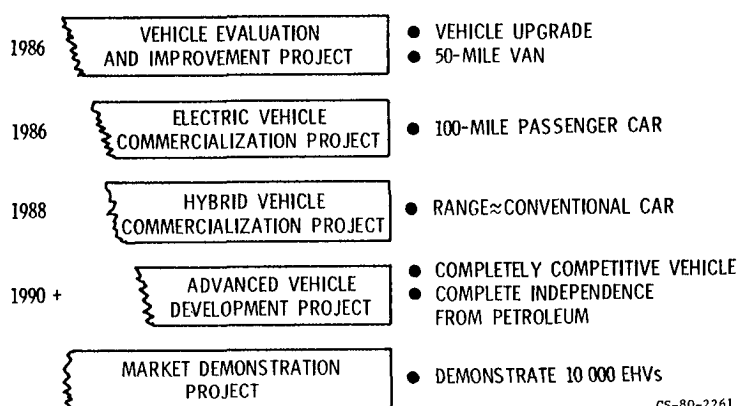


Figure 2

Problems with Electric Vehicles

The major inhibitor to the growth of electric vehicles at the present time is that they lack the range and performance that the consumer expects from an automobile. Studies of automobile use patterns (fig. 3) show that a range of about 100 miles per day would be optimum for maximum market penetration of an electric vehicle. The market potential increases until a range of 100 miles is reached and decreases beyond that point because the cost and weight penalties associated with the extra batteries required to produce the incremental range increase cannot be justified by the small additional segment of the market that would be served by such a vehicle. If we compare that 100-mile requirement with the capability of existing electric vehicles at the start of the DOE program, as shown on the lower right in figure 3, we see that only a small fraction of existing vehicles even approach this range. The envelope shown in the figure encompasses the range at various speeds of all vehicles reported in the literature at that time. The two lines shown on the figure represent actual test results of approximately 23 different vehicles tested by NASA as part of an overall electric and hybrid vehicle state-of-the-art assessment. The four best vehicles as represented by the upper line only exceed the 100-mile-range goal at very low speeds, approaching 25 miles per hour; the average for all the other vehicles tested, shown by the lower line, does not come close to the goal.

Because the market for electric and hybrid vehicles is presently so limited, we find that today's industry consists primarily of small entrepreneurial manufacturers. These companies are generally handicapped by a lack of production facilities, limited engineering staffs, and, because of the small

PRESENT TECHNOLOGY INSUFFICIENT TO STIMULATE LARGE MARKET

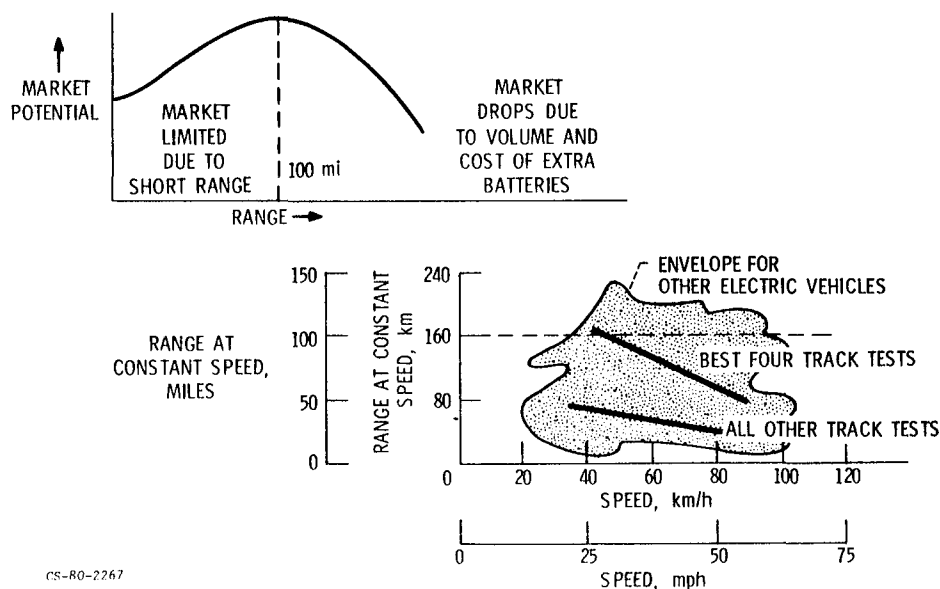


Figure 3

market they represent, insufficient leverage on the suppliers. In addition, these companies are facing a market that is going to grow at a rate that can only be described as uncertain at present, as well as a shortage of capital with which they might expand production facilities or improve their products. Therefore the challenge faced by DOE in the Electric and Hybrid Vehicle program is to find ways to maintain the viability of the present industry, to accelerate the development of the market, and to stimulate investment by those companies that have the potential for mass production, which is required in order for electric and hybrid vehicles to have a significant effect on the Nation's petroleum consumption.

Solving the Problems

These challenges are being met in several ways: Some companies have received direct support from DOE to improve the vehicles that they produce. Funds are being provided to purchase vehicles for the Market Demonstration project. Planning grants have been made available to assist small manufacturers in preparing proposals, and a loan guarantee program to help manufacturers expand their production plants in getting under way. The Market Demonstration project and its associated public awareness activities are intended to stimulate market development. The DOE is also supporting technology development that will lead to better vehicles. And, although investment risk is still high, ways are being sought to stimulate private investment in electric and hybrid vehicle production, perhaps by joint cost-shared commercialization projects. The next figures illustrate how this is being done.

Market demonstrations are an important part of the DOE program at present. As shown in figure 4, DOE has established performance standards for electric and hybrid vehicles that can be purchased for demonstration projects and has selected a sizeable number of site operators, each of whom is willing to participate on a cost-sharing basis with the Government and has agreed to operate a fleet of the minimum acceptable size. The site operators purchase vehicles from the manufacturers, thus providing an important source of capital to the manufacturers. In addition, DOE has established a loan guarantee program to help manufacturers expand their production capabilities. The money comes from a revolving fund that can guarantee loans of up to \$3 million for this

ELECTRIC AND HYBRID VEHICLE PROGRAM - MARKET DEMONSTRATIONS

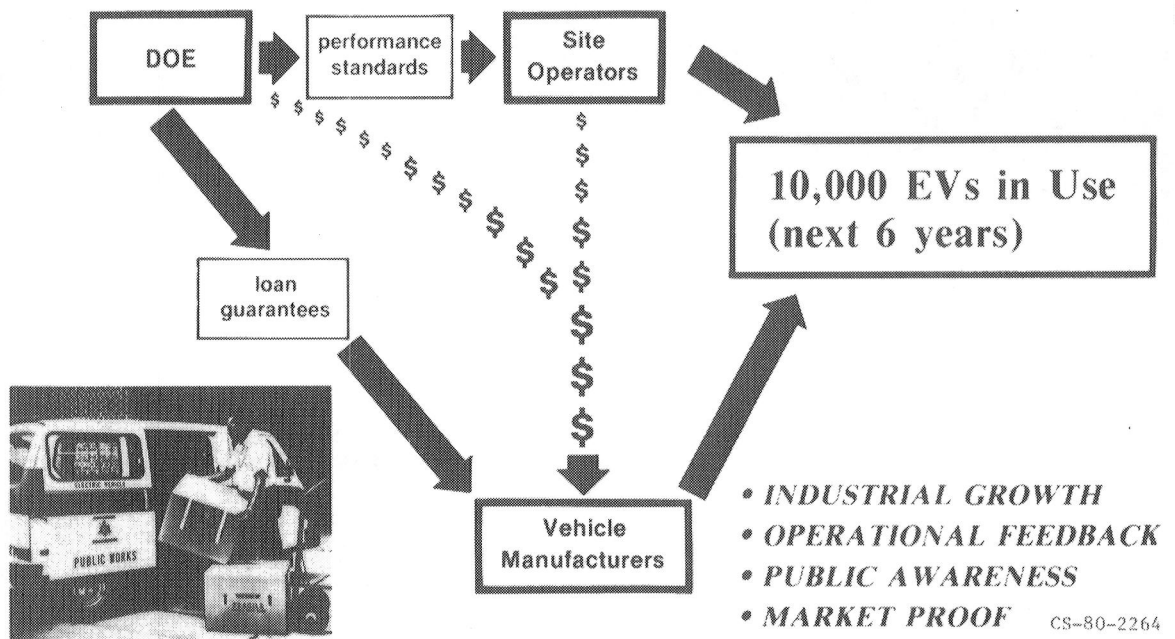


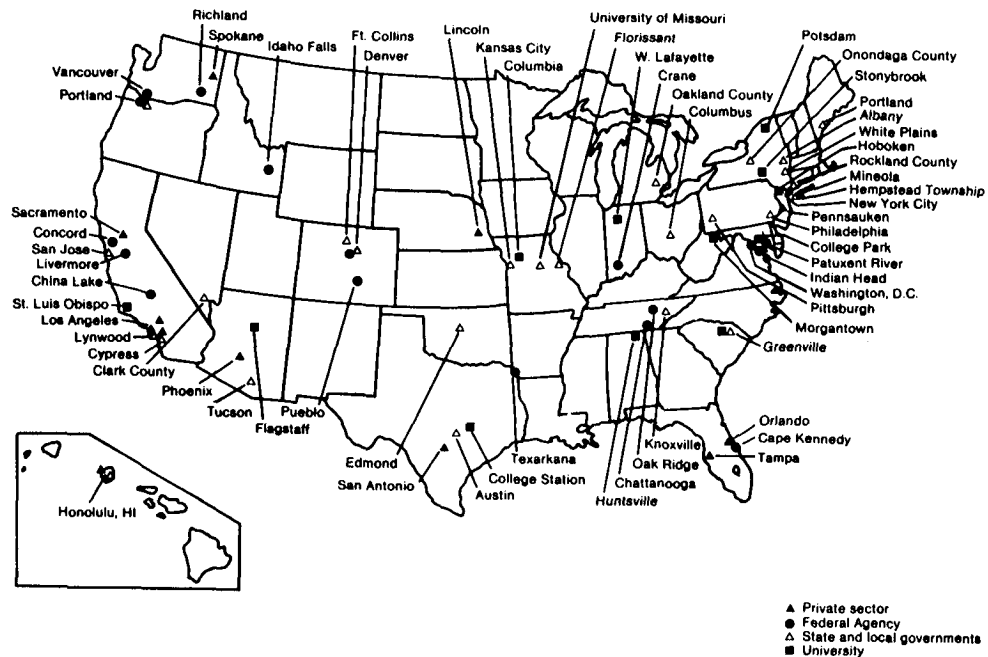
Figure 4

purpose. It is anticipated that within the next 4 years approximately 10 000 electric vehicles will be placed in service through the Market Demonstration project. Although hybrids can also be purchased for the project, at present none are commercially available.

The locations of the various demonstration sites around the country are shown in figure 5. There are four types of sites: public sector demonstrations, Federal agencies, State and local governments, and universities. In addition to showing the suitability of electric and hybrid vehicles for "real world" applications, another important function of the demonstration project is to identify the infrastructure required to support electric vehicles in day-to-day service, much as the existence of gas stations, garages, and spare-parts warehouses supports the operation of conventional vehicles on the road today. To provide better vehicles for the demonstration program, DOE has financed product improvement projects with four manufacturers. The vehicles produced under this program have operating ranges of 40 to 50 miles per day in city traffic, which is roughly twice the range of similar vehicles built in 1976. They also have greater acceleration rates and higher top speeds.

Technology development is clearly going to be required in order to produce a commercially successful vehicle. The Department of Energy is using the resources of other Government agencies in order to produce this technology. The responsibility for battery research and development is vested in the Argonne National Laboratory. Major technical thrusts at present include the improvement of the lead-acid battery and the development of nickel-zinc, nickel-iron, and zinc-chlorine batteries for near-term vehicle use. Mechanical storage technology is the responsibility of the Lawrence Livermore Laboratory. They are working on flywheels and other mechanical devices for storing regenerative braking energy, as a means for extending the range of an electric vehicle. The NASA has the responsibility for the rest of the technology development associated with electric and hybrid vehicles. This responsibility is divided between two NASA centers: The Lewis Research Center in Cleveland, Ohio, is responsible for propulsion subsystems development. This includes the development of motors, motor controllers, transmissions, and controls; the identification of battery-propulsion

DEMONSTRATION SITES IN EHV PROGRAM



CS-80-2263

Figure 5

system interactions; and the development of complete propulsion systems. The Jet Propulsion Laboratory in Pasadena, California, is responsible for vehicle system technology. JPL's activities include mission analysis, aerodynamic drag reduction, rolling resistance reduction, mass reduction, and the integration of the battery and propulsion system into a complete vehicle.

Much has been accomplished in the 3 1/2 years since the passage of Public Law 94-413, but much still remains to be done in order to make the electric vehicle a viable transportation option for our country.

JPL's Electric and Hybrid Vehicles Project—Project Activities and Preliminary Test Results

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It is clear that energy in America will become more expensive and more scarce, quite possibly to major crisis proportions in the late 1980's and in the 1990's. Petroleum fuel will certainly become the most critical element in the energy mix, largely because the United States is dependent on dwindling and interdictable foreign sources for an increasingly large share of its oil.

Since roadway vehicle operation accounts for 25 percent of the country's total petroleum use, there is obvious value in reducing gasoline use by cars and light trucks, even if this brings about no reduction in total U.S. energy consumption. However, a realistic assessment suggests that the private automobile is too deeply entrenched in the National culture and transportation scheme to be readily eliminated as a primary means of transportation for the average citizen, even as gasoline prices continue to rise dramatically.

A partial but important solution seems to be the development of light vehicles powered by energy sources other than petroleum. Electric and hybrid electric-gasoline vehicles are prime candidates for this task, largely because electricity is a source now conveniently available for the average American.

In 1976, the Department of Energy (DOE) began implementing its electric and hybrid vehicle program at Caltech's Jet Propulsion Laboratory. The structure and goals of the Electric and Hybrid Vehicle System Research and Development project are given in figure 1.

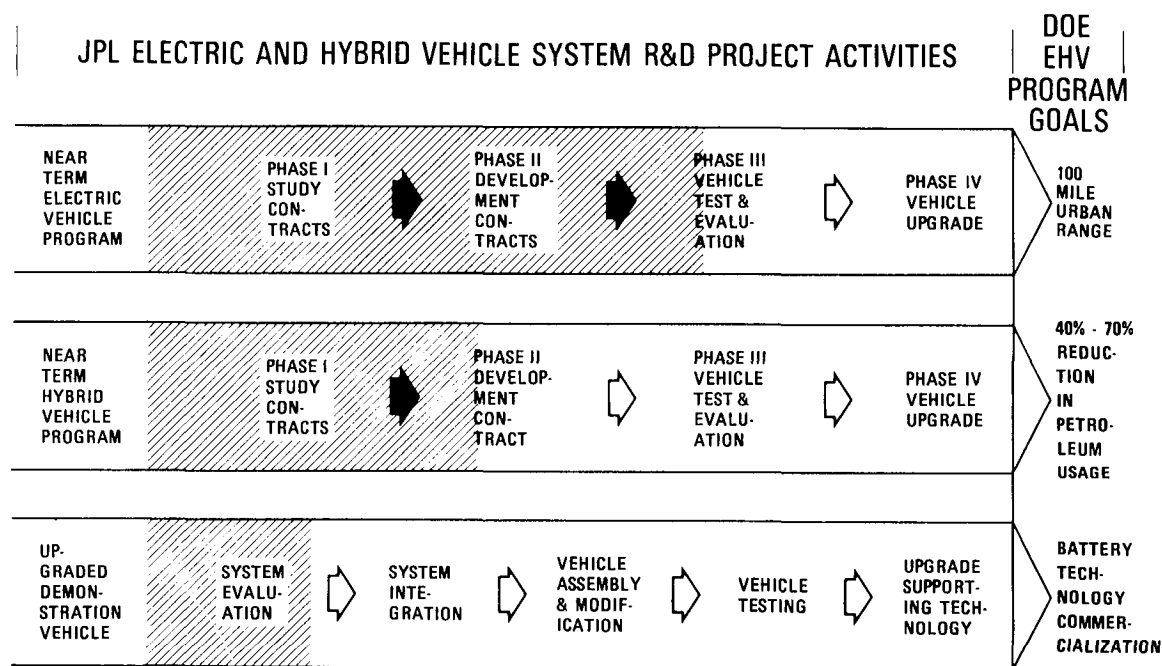


Figure 1

Hardware

Near-Term Electric Vehicles

Table I shows the state of the electric vehicle art in 1976 and the DOE goals for 1980. They are stringent, particularly the requirement for a 75-mile range. Two contractors have developed vehicles intended to meet these goals: Garrett AiResearch and General Electric Corp. The results of their efforts so far are set forth below.

Garrett AiResearch.—Garrett's vehicle is a four-passenger car that is flywheel assisted and battery powered and uses an all-plastic body. It incorporates some highly innovative approaches, as shown in figure 2. The corrugated structure in the front of the car is designed to allow a controlled, noninjury frontal barrier crash from 30 mph (fig. 3).

The batteries are housed in a central tunnel extending into the passenger compartment much like the drive shaft tunnel in today's gasoline-driven cars. Figure 4 shows the battery tunnel open and the batteries being rolled out. The batteries can be disconnected and removed from their carriage in approximately 30 minutes.

Figure 5 shows the Garrett vehicle flywheel, highlighting its construction. It is composed of nine layers of ribbon: a single inner layer of S2 fiberglass, four layers of Kevlar 29, and four outer layers

TABLE I.—STATE OF THE ART AND OBJECTIVES OF
THE NEAR-TERM ELECTRIC VEHICLE PROGRAM

	Presently available	Near-term (1980 objectives)
Range, miles	30	75
Top speed, mph	40	60
Acceleration (0 to 30 mph), sec	25	9
Safety standards	Essentially none	All FMVSS
Cost, dollars	Variable (3000 to 12 000)	5000 (FY 1975 dollars)
Recharge time, hr	Up to 12	6 or less

OVERALL VIEW OF GARRETT ELECTRIC VEHICLE

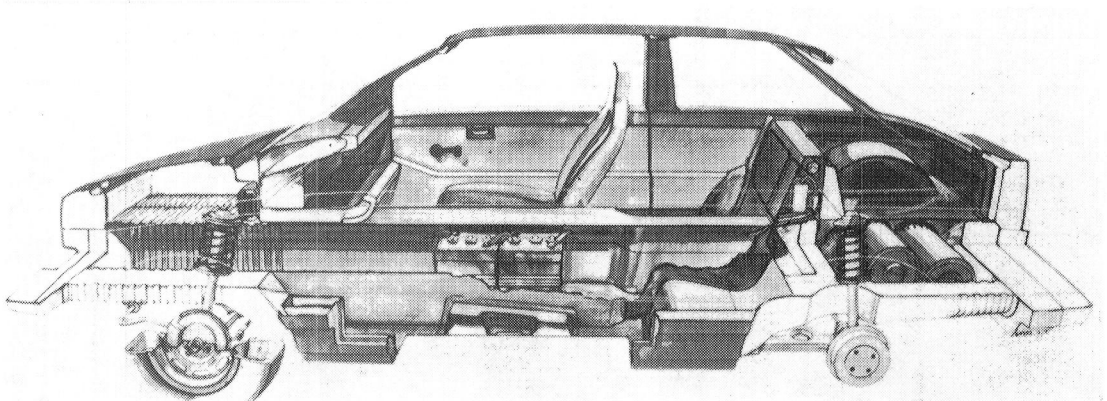


Figure 2

CONTROLLED COLLAPSE OF GARRETT ELECTRIC VEHICLE

FRONT END AT 30 mph

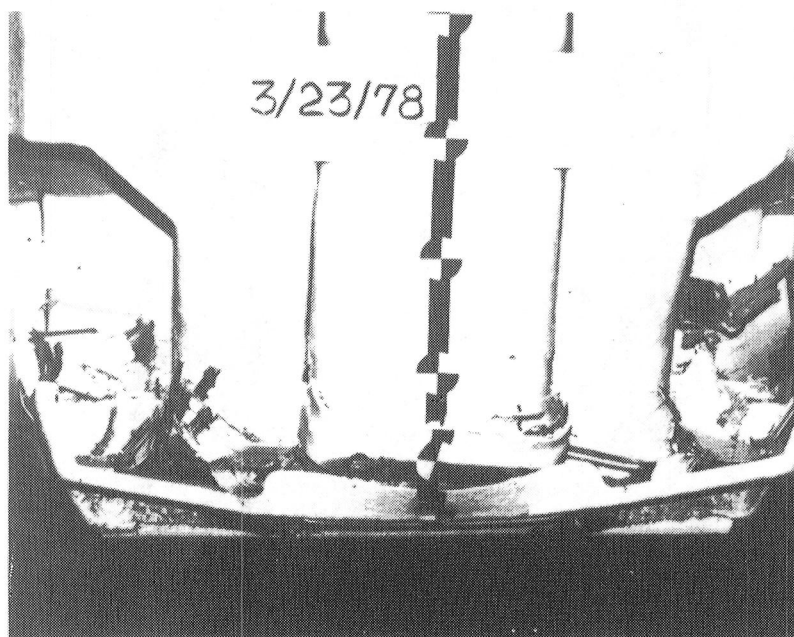


Figure 3

BATTERY CARRIAGE EXTENDING FROM GARRETT ELECTRIC VEHICLE



Figure 4

CONSTRUCTION OF GARRETT FLYWHEEL

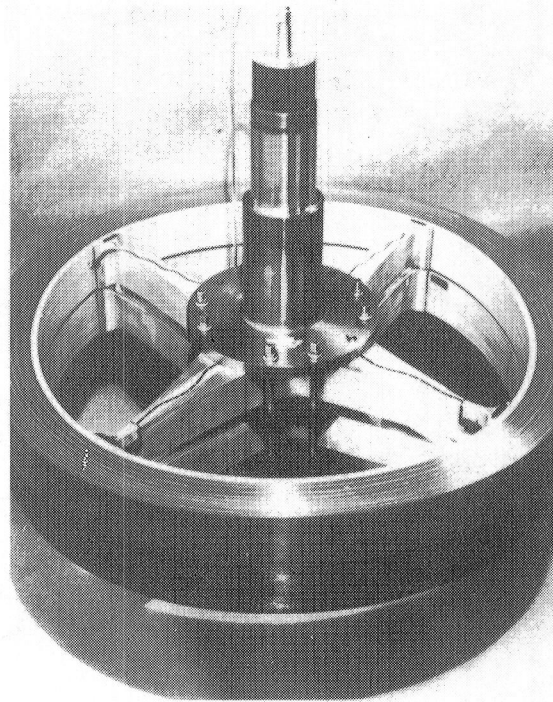


Figure 5

of Kevlar 49. Because of its layered fiber design, a high-speed failure of the flywheel causes the fibers to disintegrate into a "cotton candy" type of material (fig. 6), eliminating the danger of chunk fragmentation present in more conventional flywheels. The Garrett vehicle is now fully assembled (fig. 7) and is being tested on a dynamometer.

General Electric Corp.—The GE-designed vehicle, shown in figure 8, is a more conventional car than the Garrett vehicle. It is a four-passenger, all-metal car and uses significantly less innovative design and materials than the Garrett vehicle. It has front-wheel drive and a front motor, much like conventional compact cars. The batteries, as in the Garrett vehicle, are housed in a center tunnel.

Figure 9 shows the GE car in construction. It uses unit body construction, very similar to today's compact cars and therefore easily adaptable to current assembly-line construction. Figure 10 shows the underside of the GE car with the batteries and battery tray on the floor below the car. It is more difficult to install and remove the batteries from the GE car than from the Garrett car, largely because the GE car must be elevated on a lift to allow removal of the batteries. However, the GE car employs a central watering system so that batteries do not have to be removed from the car to add water. The GE car's shell is very stylish, as evident in figure 11. It is also quite functional: Its aerodynamic design gives it a drag product of 5.8 ft^2 (vs 10 ft^2 for the equivalent Volkswagen Rabbit). Other test results are as follows:

- (1) Range with 300-lb payload
 - (a) J227a schedule D, 74 miles
 - (b) Constant 45 mph, 92 miles
 - (c) Constant 35 mph, 123 miles
- (2) Top speed, 71.4 mph
- (3) Acceleration
 - (a) 0 to 30 mph, 8.7 sec

GARRETT FLYWHEEL TESTED TO DESTRUCTION

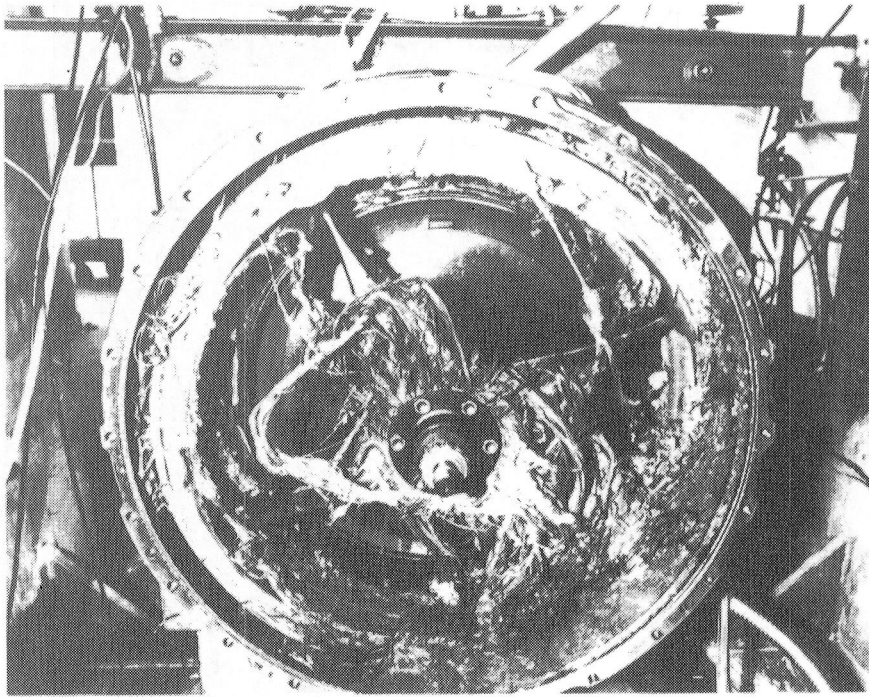


Figure 6

BODY STYLING OF GARRETT ELECTRIC VEHICLE



Figure 7

OVERALL VIEW OF GE ELECTRIC VEHICLE

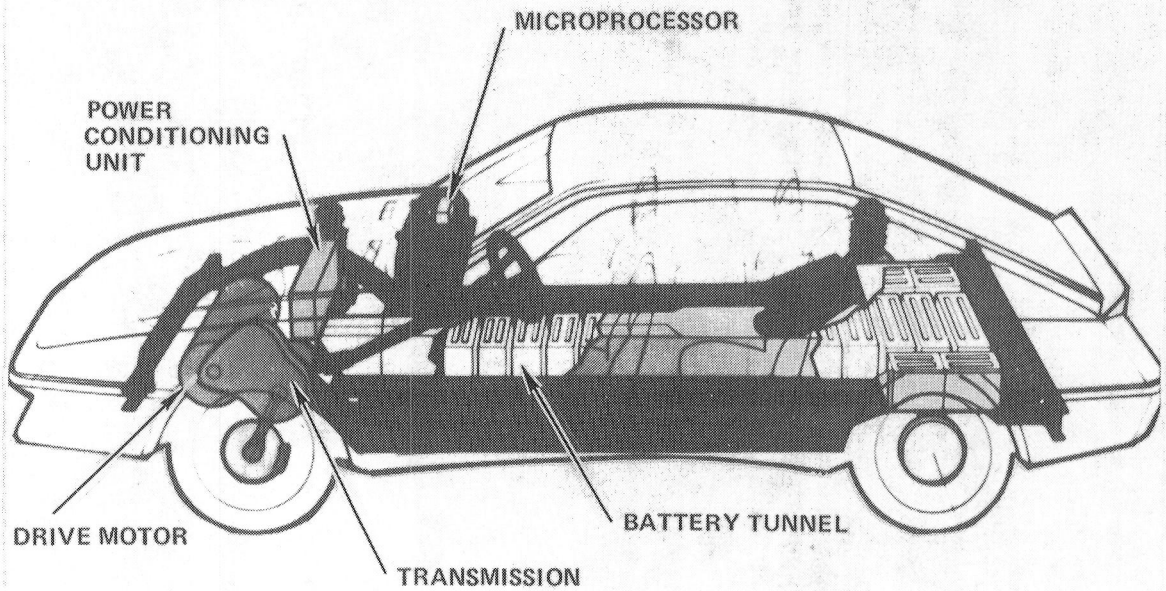


Figure 8

GE CAR IN CONSTRUCTION

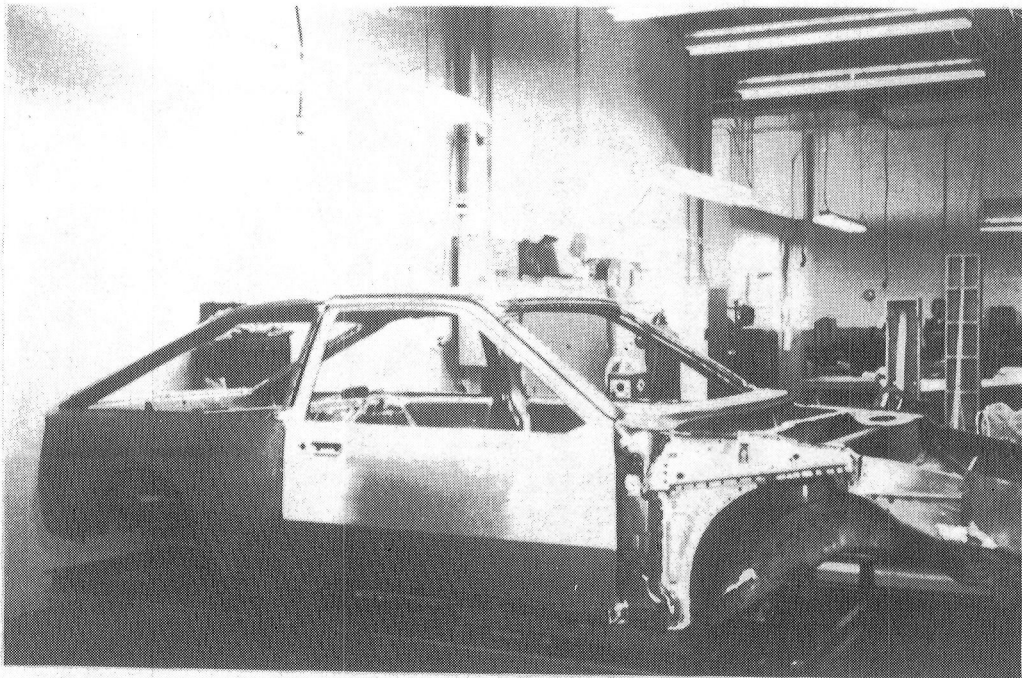


Figure 9

GE CAR WITH BATTERY TRAY REMOVED

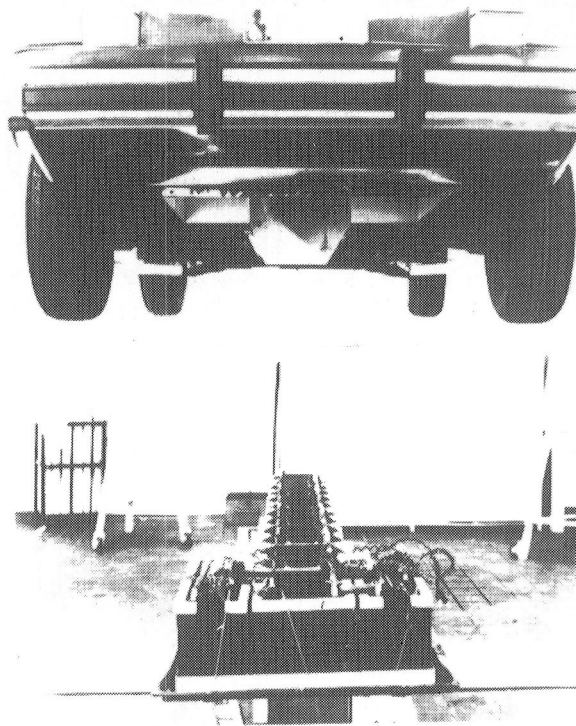


Figure 10

BODY STYLING OF GE ELECTRIC VEHICLE



Figure 11

- (b) 25 to 55 mph, 21 sec
 (4) Gradeability, 18% grade for 45 sec

Near-Term Hybrid Vehicles

Phase II of this program, the detailed design and fabrication phase, has just begun. Phase I, the study phase, was conducted largely by General Electric, South Coast Technology, MiniCars, and CR Fiat. Results of Phase I from all four contractors indicate that a parallel hybrid is a better choice for implementation than a series design. Parallel refers to a design in which both the electric motor and the internal combustion engine may directly power the drive wheels. In a series arrangement, only the electric motor directly powers the wheels, the heat engine's function being only to energize the motor. Table II shows the specifications for the near-term hybrid vehicle.

TABLE II.—NEAR-TERM HYBRID VEHICLE
 SPECIFICATIONS

Speed capability, km/h	
Cruise	90
Maximum.....	(a)
Acceleration time, sec:	
0 to 50 km/h.....	6
40 to 90 km/h.....	12
Gradeability:	
Speed on 3-percent grade, km/h	90
Minimum duration, km	1.0
Payload:	
Number of passengers.....	5
Cargo capacity, m ³	0.5
Total payload, kg	520

^aNot specified.

In the GE vehicle shown in figure 12, the electric motor and the internal combustion engine both feed into the same transmission, which drives the two front wheels. The GE car is relatively large at 5-passenger capacity; its size illustrates a fundamental difference between electric and hybrid vehicles. An electric vehicle cannot accommodate more than 4 passengers because of limitations imposed by energy storage. The GE car is approximately the size of today's "A-body" cars such as the GM Malibu.

Upgraded Demonstration Vehicles

Each experimental vehicle being tested by the EHV project will be tested with the batteries installed in it as delivered. When that testing is completed, each car will be tested with nickel-iron, nickel-zinc, lead-acid, and zinc-chlorine batteries.

Figure 13 shows the South Coast Technology VW Rabbit being tested with Westinghouse nickel-iron batteries. Note that the tests are being conducted with the batteries adjacent to the car rather than in it. Figure 14 shows the SCT Rabbit being tested with ESB advanced lead-acid batteries. A summary of the test results appears in table III.

GE PARALLEL HYBRID VEHICLE

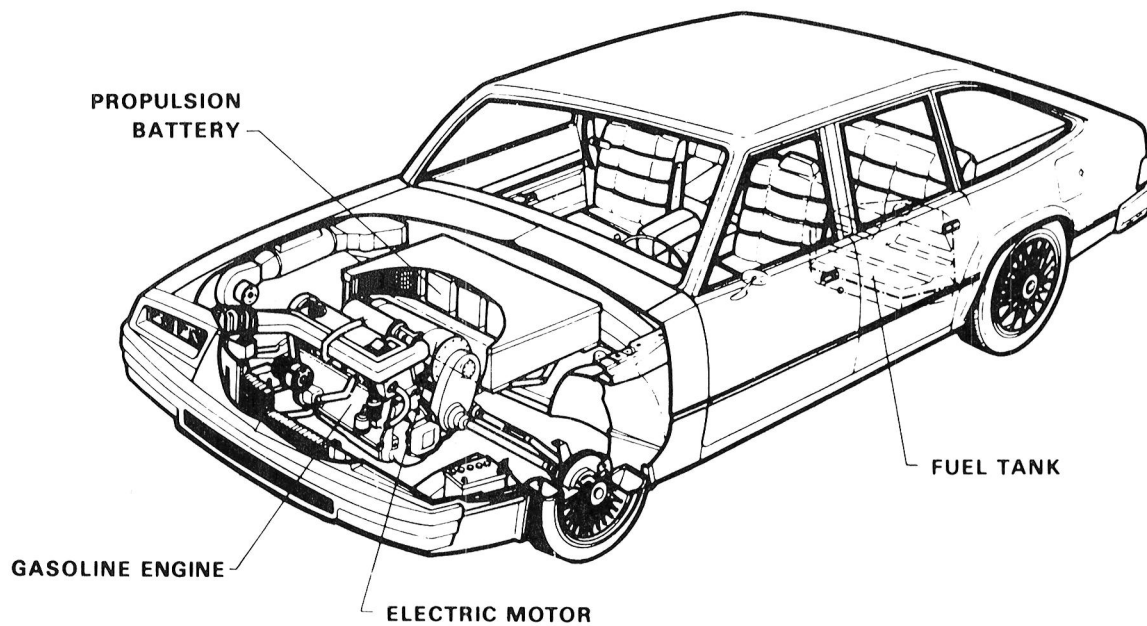


Figure 12

TESTING OF SOUTH COAST TECHNOLOGY VW RABBIT WITH WESTINGHOUSE Ni-Fe BATTERIES

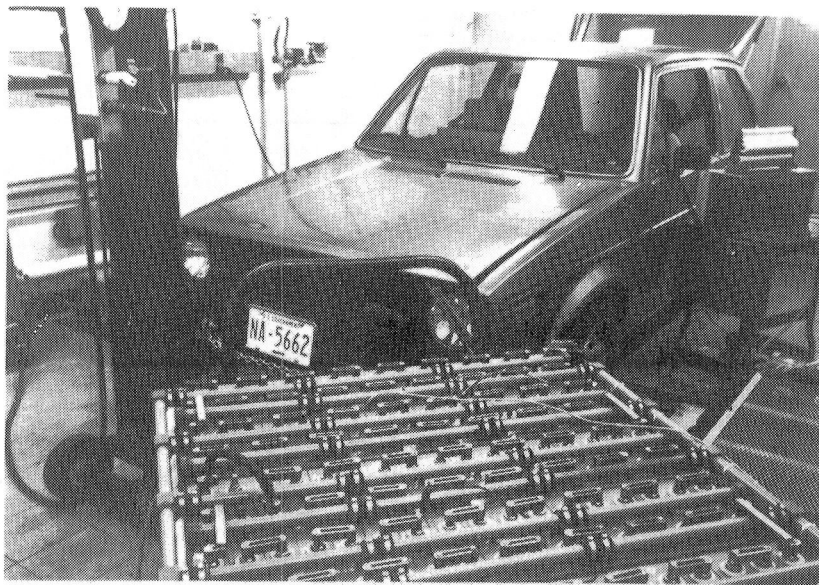


Figure 13

TESTING OF SOUTH COAST TECHNOLOGY VW RABBIT WITH ESB ADVANCED Pb-ACID BATTERIES

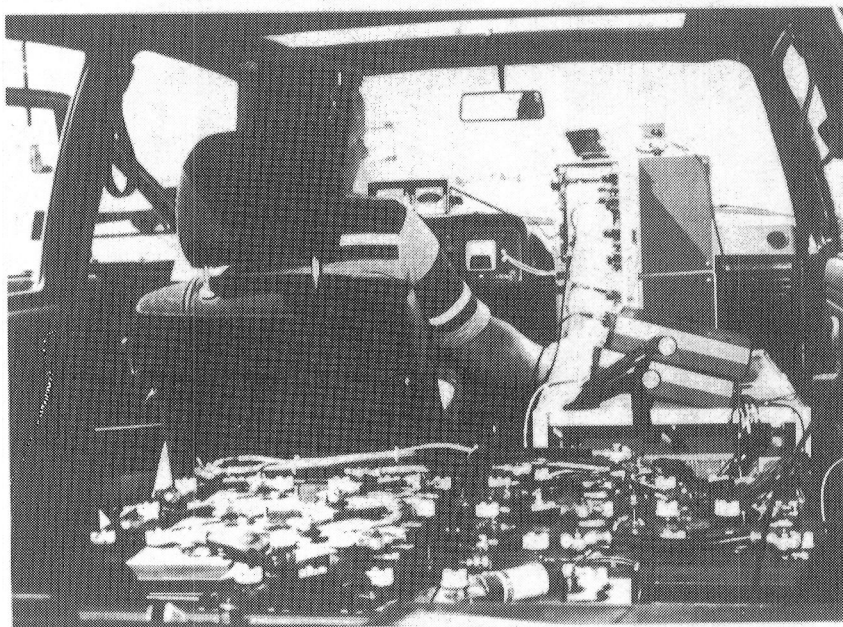


Figure 14

TABLE III.—COMPARISON OF BATTERY PERFORMANCE

Battery type	Power, kWh	Cycle life	Vehicle range (D-cycle) ^a , miles	Recharge time, hr
Lead-acid	18	40	36	10-12
Nickel-zinc	26	8-10	49	(110 V, 30 A)
Nickel-iron	24	(b)	48	5-6
Zinc-chlorine	^c 36	1000	^c 105	(220 V, 30 A)

^a D-cycle = Stop-and-go driving test.

^b Unknown.

^c Estimated.

Battery Test Results

The SCT vehicle near-term battery tests on the JPL dynamometer have been completed, and the results are presented here. However, at the time of this paper, the other 2 × 4 vehicles (two wheels in front, four in the rear to support the battery pack) had not completed the testing program for various reasons, and only limited baseline test data were available.

The SCT vehicle was fairly reliable in over 6500 km (4000 miles) of testing at JPL. Yet the motor required replacement, and intermittent problems with the controller hampered normal operation early in the test program. The SCT vehicle has exhibited substantial reduction in energy consumption

over the testing period, attributed to vehicle break-in (i.e., reduction in rolling resistance and drivetrain losses). The break-in period is continuing after 9000 total driven kilometers though the drop in energy consumption in identical tests appears to be leveling off. Because of this new vehicle break-in characteristic, the range of the SCT vehicle should not be viewed as the ultimate comparator of the near-term batteries. The apparent energy density exhibited by the batteries in each of the tests, which is less directly affected by the differences in vehicle energy consumption, would be a fairer comparison.

Results obtained from testing the SCT vehicle with both the baseline and near-term batteries are presented in the following sections.

Maximum Acceleration

The results of the maximum-effort acceleration tests, which were conducted at Edwards Air Force Base, California, are

- (1) 0 to 48 km/h (30 mph) in 9.8 to 11.4 sec
- (2) 0 to 72 km/h (45 mph) in 21.1 to 24.9 sec

These results show that the acceleration capability of the SCT satisfies the 2×4 program requirement of 0 to 48 km/h in 11 seconds and the J227a "D" cycle acceleration requirement of 0 to 45 mph in 25 seconds.

Constant-Speed Results

The baseline lead-acid battery supplied with the SCT vehicle (ESB XPV-23) performed consistently throughout the testing period. The 35-mph test produced a range of approximately 80 miles. The range dropped to about 44 miles at 55 mph, reflecting the higher road load and lower net energy output of the battery at higher power levels (i.e., "soft" discharge capability). The battery supplied approximately 15 kWh in the 35-mph range test, with a constant power demand of about 6 kW. However, the energy capacity was reduced by almost 25 percent to approximately 12 kWh when tested at the higher power requirement (13 kW) of the 55-mph test. The results of testing the SCT vehicle at constant speeds with the baseline lead-acid battery as well as the near-term batteries are shown in table III.

The ERC nickel-zinc battery substantially increased the range of the vehicle at 35 mph to 121 miles (initially); but when tested at 55 mph, the battery produced a negligible improvement over the baseline battery. The battery was found to be quite "soft" compared to the baseline lead-acid battery, with the energy capacity reduced by 54 percent in a 55-mph test when compared to a 35-mph test (21.7 kWh at 35 mph vs 9.9 kWh at 55 mph). In the same tests the ampere-hour capacity dropped by a like amount, with the battery yielding 210 Ah in the 35-mph test versus 101 Ah at 55 mph.

The Yardney nickel-zinc battery exhibited a very "hard" discharge capability. The energy capacity dropped only 6 percent, from 21 kWh to 19.7 kWh, in 35-mph versus 55-mph tests. Hence, the Yardney battery substantially increased the 55-mph range to 84 miles (up 91 percent over baseline) as well as the 35-mph range, which was boosted to over 126 miles (up 58 percent).

The nickel-iron battery developed by Westinghouse was also relatively "hard," with the energy capacity reduced by 14 percent in the 55-mph test (17 kWh) when compared to the 35-mph test (19.8 kWh). The SCT vehicle with the nickel-iron battery went over 121 miles at 35 mph and approximately 76 miles in the 55-mph range test.

The lead-acid battery supplied by Globe-Union (the EV2-13) produced a noticeable improvement over the baseline lead-acid battery but suffered from a comparatively "soft" discharge capability. The range at 35 mph was 117 miles, with 18.6 kWh discharged. The range dropped to 58 miles at 55 mph, and 27 percent less energy (13.5 kWh) was obtained from the battery.

Because of the early state of development of the near-term nickel batteries, the manufacturers had not optimized the details of recharging and in some cases varied the procedure during the course of

the test program based on interpretation of test results. In the case of the ERC nickel-zinc battery, the range in ampere-hour capacity was also a result of cell degradation.

Battery Behavior

The baseline lead-acid battery pack was found to be quite consistent in terms of repeatability and efficiency as evidenced by the data presented previously. There were no obvious signs of self-discharge. However, three of the original 18 batteries appear to have degraded to failure (battery voltage below 3 V when battery pack is fully charged) after approximately 50 charge-discharge cycles. The fact that the batteries were subjected to an equalization charge after each deep discharge to obtain repeatability could have been a factor in the failures.

The ERC nickel-zinc battery exhibited poor cycle life, experiencing significant performance degradation after a limited number of charge-discharge cycles. Over the 2-month testing period the battery was subjected to 10 charge-discharge cycles at JPL. The energy capacity dropped 28 percent in 35-mph range tests and 41 percent in the J227a "D" cycles.

The Yardney nickel-zinc battery has performed quite well to date; however, in life cycle testing under the Technology Demonstration program at Argonne National Laboratory, Yardney modules experienced a cycle life of less than 30 cycles.

The Westinghouse nickel-iron battery has experienced no performance degradation; however, several problems were encountered during the test period. The state of development of the electrolyte circulation system made it impossible for the battery to be installed in the vehicle. A large volume of hydrogen is generated during charging, compared to other battery types, and requires special venting. Six of 90 cells have failed. Five failures were due to faulty assembly, and the sixth is under investigation.

The Globe-Union EV2-13 has performed consistently throughout the testing period with no obvious signs of degradation.

Conclusions

The near-term batteries demonstrated significant range improvement relative to current lead-acid batteries. The increases in range were due to improved energy density and ampere-hour capacity, with relatively small weight and volume differences. The effect of charging procedure on battery efficiency, performance, and lifetime remains unclear at this time. The nickel-iron battery requires a substantial development effort in packaging the circulating electrolyte system and handling of the generated hydrogen volume before the battery can be successfully integrated into demonstration vehicles. The nickel-zinc batteries tested suffer from short cycle life.

The 2×4 vehicles also require further refinement in the efficiency and reliability of the propulsion systems in order to operate successfully in the Department of Energy's Electric and Hybrid Vehicle Technology Demonstration program.

Coal Gasifier Cogeneration Powerplant Project

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Until about a generation ago, stationary sources of power and heat—whether utility, industrial, residential, or otherwise—generally relied on coal as their fuel. This practice continued until the 1950's, when plentiful supplies of low-cost oil and natural gas almost entirely displaced coal. New power and heat plants were constructed, and many existing plants converted, to use these cleaner, more easily handled fuels. Conversions were commonplace by the 1960's, with the trend accelerated by the Nation's increasing environmental concerns. The process continued without letup into the first years of the past decade.

The OPEC oil embargo of 1973 created a startling awareness of a growing vulnerability: an increasing dependence on a dwindling supply of insecure and expensive foreign petroleum. For this reason the United States has been challenged to find a suitable way to return to coal as a significant factor in our fuel mix for power and heat. This is particularly so because America's domestic coal reserves are greater than those of any other nation in the world and exceed, on an energy content basis, the world's known reserves of oil.

The revival of coal use must be carried out in a manner consistent with both the spirit and the letter of justifiable environmental concerns. This is especially difficult for the Eastern States, including Ohio, where high-sulfur coal is the predominant variety.

The NASA Lewis Research Center is a typical example of present fuel usage in power and heat generation. Natural gas is used to fire boilers at the Center to provide steam for heating. Electric power is purchased from the Cleveland Electric Illuminating Company (CEI).

As a step toward dealing with America's future energy needs, National energy policy dictates that Government buildings and installations conserve natural gas and oil and, wherever practical, convert to coal in an environmentally acceptable manner. NASA Lewis is now investigating an approach to meet these requirements and, at the same time, to undertake demonstration of technology that could substantially benefit both industry and utility users and also the high-sulfur coal producers of the country.

National Energy Policy

National Energy Policy is directed toward conservation of oil and natural gas. Specifically, Public Law 95-620, the Power Plant and Industrial Fuel Use Act of 1978, prohibits new oil or gas firing for major fuel-burning installations and encourages the conversion to coal in existing facilities where practicable. The National policy is clearly aimed at the expanded use of coal in an environmentally acceptable manner. This is particularly difficult for potential users of high-sulfur coal because of the emission of sulfur oxides and the potential formation of so-called acid rain.

In attempting to meet these National objectives we have established a set of requirements with respect to the use of coal in a cogeneration mode of operation. Since we will likely have to buy coal on the spot market—as is the case with most other small coal users—we have established the requirement to burn not only high-sulfur coal, but also a wide variety of coal types and qualities. In

addition, these coals must be burned in an environmentally acceptable manner that minimizes not only stack emissions of particulates, sulfur, and nitrogen oxides, but also other controlled trace elements and all other waste streams.

We must also meet our seasonal steam heating demand, which varies from a summer low of 20 000 pounds per hour to a winter peak of 100 000 pounds per hour. NASA Lewis, along with other Government agencies and industry, has an ongoing need to conserve energy. This added requirement would not be met by simply substituting coal for oil or gas.

The requirement of satisfactory payback time is also of vital importance for Lewis. For industry it is essential.

The powerplant must use state-of-the-art technology for two reasons. First, the latest technology will be more efficient and reliable. And second, it will be more adaptable to future improvements with growth potential. This is particularly true for turbomachinery and combustion components.

And, finally, there is the critical requirement (particularly important to small users) of having waste products that are suitable for sanitary landfill without further treatment. Waste products must be disposable without treatment at reasonable cost and with minimum handling and logistics.

Approaches for Use of High-Sulfur Coal

There are a number of approaches that can be considered for the use of high-sulfur coal. Atmospheric fluidized-bed combustion is currently being used in some applications. Pressurized fluidized beds have not yet been commercialized. In either concept the coal is intimately mixed with a sorbent—usually limestone for the atmospheric fluidized bed. The coal is desulfurized directly in the fluidized bed, with the resultant formation of calcium sulfate. This approach requires materials handling of limestone as well as coal as feedstock and handling of ash and spent sorbent as waste products. This combination of waste products must be removed from the site and permanently disposed of.

Flue gas desulfurization has been adopted by many utilities with varying degrees of success. With high-sulfur coal the stack or flue gases—products of combustion containing sulfur oxides—are scrubbed with water and a sorbent to form a sludge waste product. This approach typically exhibits problems of reduced reliability and availability, increased water use, increased energy use, and difficulty in handling and disposing of sludge wastes. In addition, the scrubbers are a significant parasitic electric load that degrades overall powerplant efficiency.

Other approaches for high-sulfur-coal use are being studied but are not yet commercialized. A promising approach is coal beneficiation—a technique that precleans and/or pretreats the coal to insure environmental acceptance of the combustion products.

Gasification is the approach that is under consideration for application at the NASA Lewis site. The rationale for this selection is as follows: It is the only process that can use high-sulfur coal with proven, commercially available acid-gas-removal cleanup techniques. In addition, since gasification requires only partial combustion, the consequent removal of acid gas (hydrogen sulfide) involves treatment of only a small fraction of the volume that would be treated by flue gas desulfurization methods. Under some conditions this fraction is as low as 1 percent.

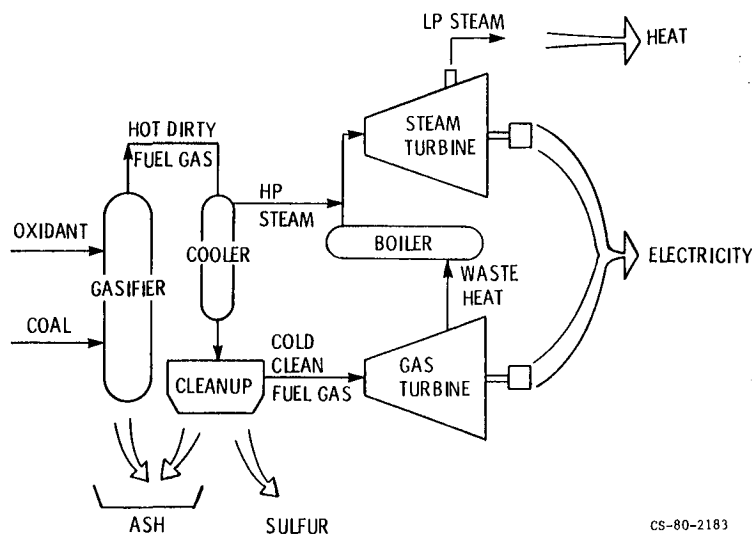
Some gasification techniques have the potential for accepting a wide variety of coal types and qualities. This is particularly important for small coal users who may have to buy on the spot market. Waste-handling problems are minimized because the low product volumes (ash and elemental sulfur) are suitable for direct landfill use. Also there is good potential for achieving gaseous fuel emission standards, rather than solid (coal) fuel standards. This is due to the need for particulate and sulfur cleanup before gas turbine combustion to minimize corrosion in the turbine hot section. Also, when low-Btu gas is burned, the products of combustion—specifically oxides of nitrogen—are well within the new-source stationary emission standards without additional treatment techniques.

The potential for high electrical conversion efficiency exists when gasification is integrated with a combined-cycle powerplant. In addition, the cogeneration option can provide significant gains in coal utilization efficiency by using waste heat from the gas turbine to raise steam for process heating.

Coal Gasifier Cogeneration Powerplant Concept

A simplified schematic diagram of the concept is shown in figure 1. Coal and oxidant are reacted in a pressurized gasifier to generate a hot, dirty fuel gas whose temperature depends on the gasifier type and can range from 700° F to about 2600° F. The sensible heat of the fuel gas is recovered in a cooler by raising high-pressure steam. The cooled fuel gas is then routed to a commercial sulfur cleanup process. Cold fuel gas of "pipeline quality" cleanliness is then combusted in a gas turbine and produces electricity and a high-temperature combustion product exhaust. The exhaust is used to generate high-pressure steam in a heat-recovery steam generator. After combination with the high-pressure steam from the cooler, the total steam flow is passed through a steam turbine to generate additional electricity. By using a commercial extraction steam turbine low- or intermediate-pressure steam for heating can be removed for on-site use. In addition, it is important that the steam used for heating has performed shaft work in the steam turbine before extraction. This not only increases electrical output, but also allows the extraction steam turbine to follow steam load demand variations while the gasifier and gas turbine components operate at steady state or full load.

COAL TO GAS COGENERATION POWERPLANT CONCEPT



CS-80-2183

Figure 1

Coal Gasifier Cogeneration Powerplant Study

Study Rationale

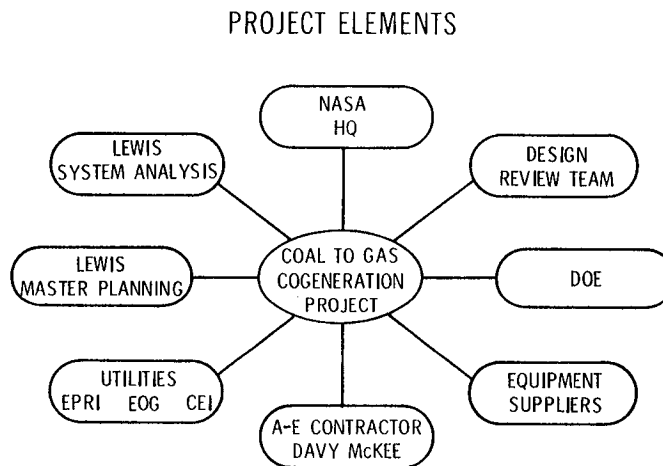
The major reasons for NASA Lewis' interest in this system concept are as follows: The National requirement to convert to coal firing is based on conserving oil and natural gas. The National need for an efficient, economically attractive option for burning high-sulfur Eastern coal exists both for industrial plants and Federal installations like NASA Lewis. It is believed that the coal gasifier combined-cycle powerplant is that option and that there is an urgent need for a timely demonstration of this technology.

In converting to high-sulfur coal firing the Lewis Research Center must modify or replace its existing steam plant. It is this confluence of needs that creates the opportunity for the Federal Government to meet National requirements and at the same time characterize and demonstrate this important technology for industry and the utilities.

Study Elements

The key groups that comprise the interactive elements of the study are shown in figure 2. The Lewis Systems Analysis Group has put to use their considerable experience in analyzing industrial cogeneration and utility systems. The Lewis Master Planning Group has the responsibility for all future facilities and their effect on the Center. The local utilities involved in the study are the Cleveland Electric Illuminating Company and the East Ohio Gas Company. The Electric Power Research Institute, because of their background in coal gasification and their interest in commercialization of large coal gasifier combined-cycle powerplants, is kept informed of the progress and results of this study.

After initial studies by the Systems Analysis Group, a competitive procurement was completed, and the Davy McKee Corporation was selected as the architect-engineer to conduct a conceptual design study to further evaluate the technical and economic feasibility of a coal gasifier cogeneration powerplant to be sited at NASA Lewis. The \$205 000 contract began December 21, 1979, and ended in July 1980. To ensure objectivity in the study results, a Design Review Team of technical specialists was appointed to provide an ongoing independent review and to prepare recommendations for NASA management. The NASA Headquarters role in this study has been to provide initial financial support and to integrate this program with energy savings and coal conversion programs within NASA.



CS-80-2407

Figure 2

Feasibility Study

The feasibility study contract elements and schedule are shown in figure 3. Initial effort was aimed at selecting a suitable site at Lewis and performing a detailed screening and selection of feasible gasifiers. From an initial list of about 35 candidate gasifiers, five were selected that best fit the evaluation criteria. A reference case baseline configuration was then subjected to an initial system capital cost estimate. Component and system selections, siting, performance, and costs were evaluated by the Design Review Team.

An important consideration of the study was powerplant size or output. The factors that affect plant size are shown in figure 4. These include available gas turbomachinery package size, acceptable coal- and waste-handling facilities and logistics, available sizes of gas particulate and sulfur removal cleanup systems, maximum steam demand for cogeneration, manpower and operating cost constraints, size-related regulations for siting and emissions, and capital cost.

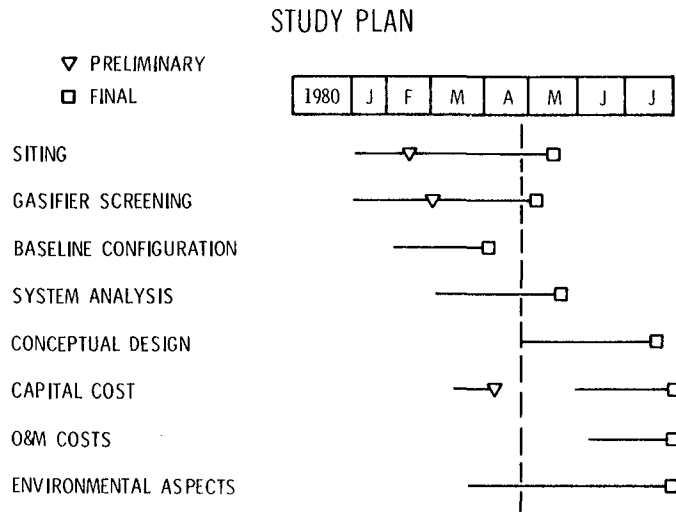


Figure 3

CS-RO-2395

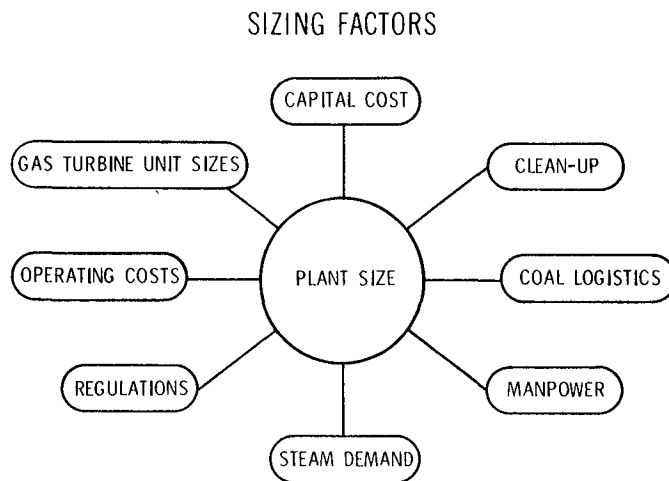


Figure 4

CS-RO-2389

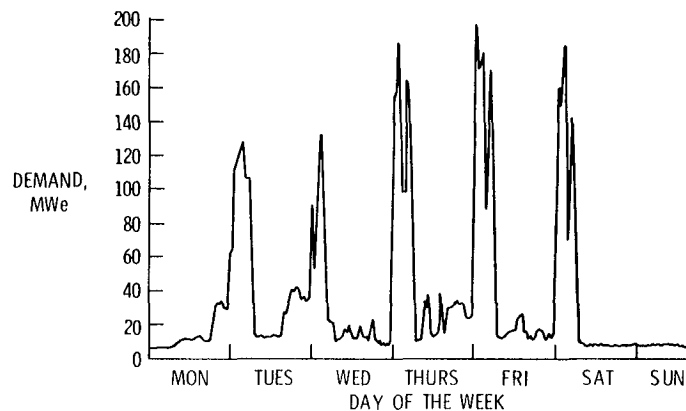
An additional size-related factor that is peculiar to the NASA Lewis Research Center is related to electricity demand, as shown in figure 5. A typical week shows a weekend load of about 5 megawatts and workday evening peaks to 200 megawatts. These high loads are due to operation of supersonic wind tunnel facilities. Evaluating these widely varying demands with other sizing factors led us to a baseline-configuration nominal output of about 20 megawatts electric.

The impact of this output is shown in the electric load duration curve of figure 6. This curve is based on an annual integration of hourly data and shows that the load will typically exceed 20 megawatts about 25 percent of the time. The upper levels of the curve are not shown but would indicate that the maximum load of about 220 megawatts is only attained for a few hours every year. During the summer, when steam demand is low (20 000 lb/hr), the extraction steam turbine generates more electricity than in the winter, when steam demand may reach 100 000 pounds per hour.

At those times when electrical demand exceeds the powerplant rating, electricity is imported from the utility. When electrical demand is less than the plant rating, electricity is available for export to

EXAMPLE OF DAILY ELECTRIC DEMAND

AUGUST 1979

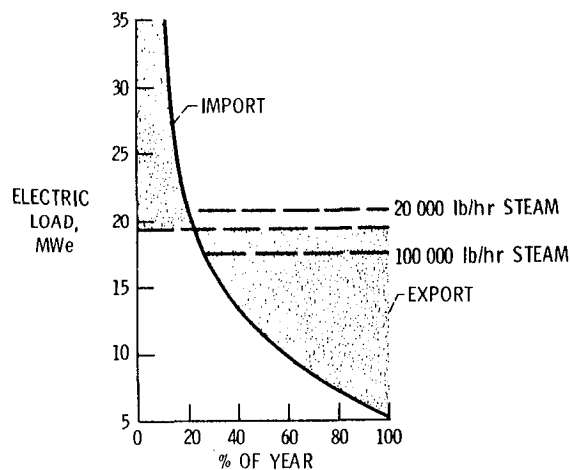


CS-80-2399

Figure 5

OPERATION OF PRELIMINARY BASELINE CONFIGURATION

20 MWe NOMINAL RATING



CS-80-2400

Figure 6

the utility grid. For a nominal 20-megawatt-electric plant rating the total energy imported is about equal to that exported, although the curve indicates that power is purchased only 25 percent of the time and sold 75 percent of the time. Also, both import and export can occur on any typical day.

The initial tasks of the feasibility study were the establishment of gasifier selection criteria and subsequent screening and selection of a baseline gasifier. Two of the key discriminators of the total of 20 used are the ability to use a wide variety of coals (including Ohio coal) and the near-commercial status of development. The candidate gasifiers that survived screening were the Westinghouse fluidized bed, the IGT U-gas fluidized bed, the Texaco entrained flow, the B&W entrained flow, and the British gas slugging fixed bed. Of these, the Westinghouse fluidized-bed gasifier was selected for the baseline conceptual design. The other major components of the powerplant—the cleanup system,

the turbomachinery, the heat exchangers, and the coal-handling equipment—are all commercially available hardware.

The heat-exchanger category includes a raw-fuel gas cooler that will cool 1850° F gas to 400° F by generating 750° F steam for use in the steam turbine. At these temperatures materials problems in the gas cooler should be minimized and should permit current commercial design practice to be used.

After all system components had been identified, a preliminary cost comparison was made between the coal gasifier cogeneration powerplant and two alternative concepts. The two alternative systems are (1) a high-sulfur-coal-fired steam plant with flue gas desulfurization (scrubber); and (2) a low-sulfur-coal-fired steam plant with an electrostatic precipitator (baghouse). Both of these alternative concepts produce steam for heating only and do not generate electricity.

The scrubber and baghouse concepts are characterized by relatively low capital costs, but both exhibit negative first-year operating savings. However, for the coal gasifier cogeneration powerplant, first-year annual savings of \$2 to \$7 million dollars are estimated—depending on both the electrical rate structure and the fuel cost scenario assumed. These savings are comparable to the total current annual utility costs for the Center.

A technical assessment of the key components of the gasifier cogeneration powerplant was made, with the following results: For the gasifier selected, a modest size increase from the current process-development unit would be required. Coal feed for the NASA Lewis powerplant will be about 120 tons per day for each of two gasifiers operating in parallel. Integration of two simultaneously operating gasifiers has not been demonstrated but is desirable to verify multiple module operation for larger applications. The gas turbine combustor must be modified for low-Btu-gas firing, and compressor and turbine flow rates must be matched. These turbine modifications do not appear to be major technical problems. The design of an integrated controls system has not been demonstrated for this system, but it is not expected to represent a major technical barrier once the dynamic and transient performance of each major component has been adequately characterized. This characterization is an important part of system demonstration. In summary, no fundamental technical feasibility issues are seen for the powerplant concept.

A preliminary environmental assessment of the concept has concluded that no barriers to environmental acceptance are foreseen. The concept will result in minimum waste-handling requirements, flue gas effluents will be well under environmental standards, and the selection of a low-Btu gasification process will allow combustion without water injection for NO_x suppression. In addition, as part of this study, we envision conducting an environmental impact assessment so as to establish a precedent for potential industrial applications.

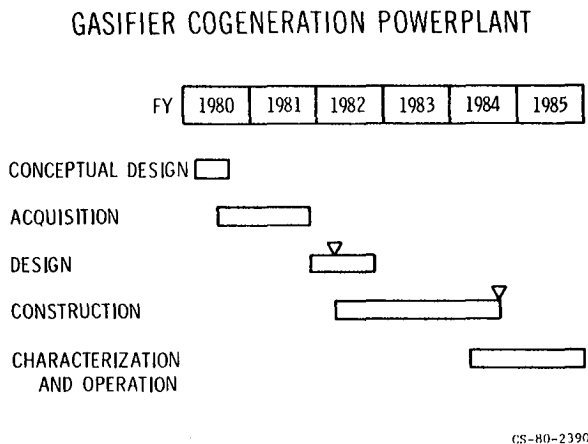


Figure 7

Study Schedule

In terms of the overall study schedule a total of 5 years is estimated from start of conceptual design to completion of system characterization (fig. 7). Included in this schedule are significant time periods for acquisition, or procurement, and for characterization of the powerplant. A 2-year system characterization time would be used to check out all components and to completely define all system operating parameters. This effort is aimed at reducing risk for subsequent commercial application and is a key part of our study philosophy.

Conclusions

To be considered as a significant coal alternative in a broad sense, the cogeneration powerplant must satisfy a variety of requirements. Some important current utility and industrial cogeneration requirements are

Utility requirements:

1. 50 Percent backout of oil by 1990
2. No new oil or natural gas primary fuel firing
3. Environmental compliance (no acid rain)
4. Siting flexibility
5. Increased reliability and availability
6. Ability to accommodate unpredictable load growth
7. Reduced construction times
8. Economic competitiveness
9. Improved efficiency
10. Growth potential
11. Flexibility

Industrial requirements:

1. Rapid payback
2. Attractive ROI
3. Ability to use wide range of coal
4. Siting flexibility
5. Minimum logistics
6. Lowest emissions potential (minimize offsets)
7. Growth potential
8. Acceptable reliability and availability
9. Minimum land requirements
10. Short construction times

The technical and economic feasibility study for a combined-cycle gasifier cogeneration powerplant to be located at the NASA Lewis Research Center has tentatively shown that most of the utility and industrial requirements can be met. In addition, the study results have provided the basis for evaluating the practicality of this powerplant, whose completion would provide a system technology demonstration that would verify the following potential benefits:

1. Ability to use a wide range of coals including Eastern high-sulfur coal
2. Minimum environmental emissions and wastes
3. High efficiency
4. Rapid modular construction
5. Siting flexibility
6. Economic attractiveness
7. Potential for repowering existing oil and natural gas utility capacity
8. Only near-term alternative with growth potential, but needs system technology demonstration

The coal gasifier cogeneration powerplant being considered will not only meet the needs of the NASA Lewis Research Center, but, at the same time, will also reduce the commercial risk for industry and utilities by fully verifying and demonstrating this important technology. The powerplant would, if funded, also represent a cooperative venture of industry and Government to accelerate commercialization so as to achieve wide-spread implementation and thereby make a significant contribution to energy independence while minimizing environmental intrusion.

The DOE Photovoltaics Program*

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Solar cells convert sunlight to electricity directly. Such photovoltaic units have no moving parts and are quiet, nonpolluting, extremely reliable, and easy to operate. Although they are still expensive, they offer a promising way to use the Sun's inexhaustible energy here on Earth.

During the past 6 years the U.S. National Solar Energy program has grown from small, experimental, research-applications efforts at the National Science Foundation and at NASA in space applications, through a technology development and applications program under the Energy Research and Development Administration (ERDA), into a large technology, applications, and industry-oriented program managed by the Department of Energy (DOE).

The early application of photovoltaic systems was in aerospace (satellite) programs, and thus the technology was developed to be responsive to the demands of the aerospace industry. The major concerns were weight reduction, radiation tolerance, conversion efficiency, and very high levels of reliability. Customized requirements for each mission allowed little standardization and forestalled any serious attempts at cost reduction.

The U.S. Department of Energy, as part of the National Solar Energy program, is now engaged in the development of technically feasible, low-cost candidate component and system technologies to the point where technical readiness can be demonstrated by 1982. The overall strategy is to pursue parallel options that continue to show promise of meeting the program goals, thus increasing the probability that at least one technology will be successful. Included in technology development are both flat-plate solar collectors and concentrator solar collectors, as well as the balance-of-system components, such as structures, power conditioning, power controls, protection, and storage. Generally, these last items are common to both flat-plate and concentrator systems, but otherwise there is considerable disparity in design philosophy, photovoltaic cell requirements, and possible applications between the two systems.

Since 1973, when the Arab oil embargo initially underscored the world's dependence on petroleum, researchers have continued their efforts to build photovoltaic devices that can extract electricity from sunlight more cheaply than conventional generators produce it from fossil fuels. That goal has not been achieved yet, but today's photovoltaic technology development shows significant progress. Cells are more efficient and less expensive than ever and promise to become more so in the future.

To summarize the progress during the past several years

(1) The price of a typical commercial solar cell array has been reduced by a factor of 3 or more. In 1975 module prices ranged from \$25 to \$90 per watt. Today, a module with similar performance and far better reliability sells for about \$5 to \$15 per peak watt (W_p).

(2) Relatively large installations are beginning to be built for both flat-plate and concentrator technologies. These will produce major new operating system experience. The Mt. Laguna Air Force Station installation, which was dedicated in July 1979, has been for the past year the largest flat-plate

* The work described in this paper was carried out or coordinated by the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the U.S. Department of Energy through an agreement with the National Aeronautics and Space Administration.

installation, rated at 60 kilowatts. The Natural Bridges National Monument installation (100 kW, flat plate) was dedicated June 7, 1980. Similarly, large concentrator technology experimental systems are now being installed. The largest in the United States is at the Mississippi County Community College in Blytheville, Arkansas, with a rating of 240 kilowatts achieved by using 40X concentrating parabolic trough collectors.

(3) Conversion efficiencies of cells based on "mature" technologies (single-crystal and polycrystalline silicon) have risen dramatically, and several are now approaching their economic optimum.

(4) The U.S. Government, and other governments around the world, have recently increased funding for research and development programs aimed at identifying new technologies and reducing cell production costs.

Because array costs are dropping, the world-wide market for photovoltaics is beginning to expand. It is envisioned that annual installed capacity will rise from last year's level of about 1 megawatt to at least 50 000 megawatts by the year 2000. By 1982 it is anticipated the market will become large enough to justify significant automated mass production of photovoltaic systems; costs will continue to decrease, but at a much faster rate. That, in turn, will open up new markets and accelerate sales. With experience and production scaleup, price goals will finally be reached, and large-scale commercial deployment of systems can begin.

This essentially describes the main thrust and objectives of the U.S. Department of Energy Photovoltaics program. This paper reports the work being done today in the United States. The efforts are diverse, as are the estimates given for the potential viability of photovoltaics as an alternative energy source, but they do have several common denominators—a worldwide need for such an alternative, strong technology development programs, and great promise.

Photovoltaic System Price Goals

The U.S. Department of Energy has developed long-range goals to ensure that photovoltaics will supply a significant amount of electrical energy to the Nation by the year 2000, at which time the President has established a National goal of 20 percent solar electric energy production capability. Formal price goals have been established by DOE for the photovoltaics program. These goals have been chosen such that, if they are achieved, it is expected that photovoltaics will make significant penetrations into the small and remote (stand alone), utility-connected residential, intermediate-load, and central-station markets.

Figure 1 shows the DOE price targets for photovoltaic collectors and systems (in 1980 constant dollars), as well as the flat-plate-collector purchase price history. Because these goals apply to both flat-plate and concentrator technologies, direct comparisons require some normalization: Flat-plate collector price goals do not include supporting structures, but such structures are an integral part of concentrator collectors. The DOE commercial readiness price goals for complete systems (in 1980 dollars per peak watt of system output) are

- (1) \$1.60 to \$2.20 per W_p for residential applications by 1986
- (2) \$1.60 to \$2.60 per W_p for intermediate-load centers by 1986
- (3) \$1.10 to \$1.80 per W_p for central stations by 1990

Photovoltaics Program Legislation

Photovoltaics RD&D Act

The National Photovoltaics RD&D Act, passed last year by the U.S. Congress, authorized the expenditure of \$1.5 billion over the next 10 years for photovoltaics research, development, and

DOE PHOTOVOLTAICS PROGRAM PHOTOVOLTAICS MODULE AND SYSTEM PROGRAM GOALS

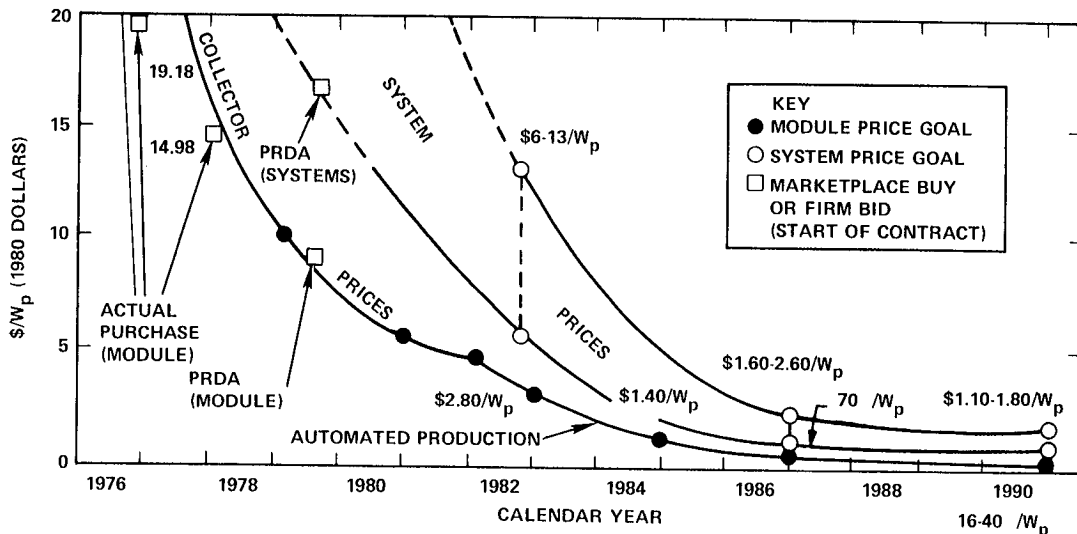


Figure 1

commercialization. This was an invitation to companies to make a market commitment to photovoltaics by investing in much-needed mass-production capacity. Funding through this legislation heavily favors research and technology development with supporting experiments for the next several years and will then gradually shift to emphasize larger, commercial demonstration projects in the field.

The Federal Photovoltaics Utilization Program

Recently, Federal legislation has been enacted to assure that photovoltaic systems are applied to various Government application sectors as they become cost effective. The Federal Government has initially authorized \$98 million over a 3-year period for the Federal Photovoltaics Utilization program (FPUP) for purchases of photovoltaic energy systems. FPUP has two immediate goals: (1) to develop the Federal market by encouraging Government agencies to incorporate photovoltaic systems; and (2) to provide marketing support to commercial solar cell and system manufacturers, whose growth is crucial to the ultimate success of the photovoltaics program. The program will initially provide for procurement of the smaller remote systems and will be broadened to include residential and intermediate-load systems.

Advanced Research and Development

The Advanced Research and Development program in photovoltaics is the responsibility of the Solar Energy Research Institute, which is operated by the Midwest Research Institute for the Department of Energy. The main thrust of this effort is to achieve technical feasibility for a variety of advanced material technologies. These technologies are intended to have the potential for achieving 10 percent conversion efficiency with a cost potential of \$0.15 to \$0.40 per W_p (in 1980 dollars) leading to systems costs of \$1.30 per W_p or less. Much of this AR&D effort is directed toward the investigation of concepts, materials, and structures leading to very low-cost solar cells with thin-film structures. Thin-film cells in particular offer high material conservation, simplified fabrication tech-

niques that can be readily automated, and the possible use of inexpensive substrates. Higher conversion efficiencies are also being sought through advanced cells for use with concentrated sunlight.

The AR&D programs in photovoltaics encompass three major areas: advanced materials and cell research, high-risk research, and research support and fundamental studies. The advanced materials and cell research effort carries the development of selected solar cell technologies through the exploratory development phase to a point where technical feasibility is achieved. The high-risk research programs are directed toward those materials and concepts that are not well developed and that are perceived to carry high risk in terms of established R&D goals. The research support and fundamental studies effort is intended to enlarge the materials and technology base and to provide the research tools needed to improve general state-of-the-art cell development.

Thin-film cell technologies being studied in the advanced materials and cell research effort include polycrystalline silicon, cadmium-sulfide-based materials and structures, amorphous silicon, and gallium arsenide. The polycrystalline silicon task is already entering the exploratory development phase. The goals of the cadmium sulfide thin-film effort are to achieve an efficiency of at least 10 percent in fiscal year 1980 and to demonstrate suitable cell stability for large-area encapsulated cells and an 8-percent conversion efficiency for small-scale arrays by the end of fiscal year 1982. Amorphous silicon is being studied to obtain an understanding of the fundamentals of the defect-state passivation process, with square-centimeter cells having 5.5 percent efficiency already being made and prospects of 10-percent-efficiency cells or better in the future. Gallium arsenide research is directed toward the deposition of films with large grain sizes, understanding the effects of grain boundaries on cell performance, and investigating different junction formation techniques. The objective of this effort is to achieve a thin-film cell conversion efficiency of 12 percent by fiscal year 1983.

High-risk research covers emerging materials, amorphous materials other than silicon, advanced concentrator concepts, electrochemical photovoltaic cells, and innovative concepts. A variety of emerging materials and device concepts are being studied that have potential in the long-range future. Low-cost technologies such as spray and screen-printing techniques using CdS/CdTe, CdS/Cu₂S, and CdS/Cu ternaries are being investigated. The photovoltaic properties of amorphous GaAs, boron, II-IV-VI compounds, and chalcogenide semiconductor glasses are being studied. Research on advanced concentrator concepts is being conducted, including the possibility of luminescent conversion and multijunction concentrator cells with potential efficiencies greater than 30 percent. The electrochemical photovoltaic cell work centers on fundamental studies of the semiconductor-electrolyte interface and semiconductor-electrolyte combination for high conversion efficiency and stability at low cost.

Activities in research support and fundamental studies include basic mechanism studies, test and measurements, technical issues, and development initiatives. Studies of basic mechanisms are intended to identify those mechanisms that limit the conversion efficiency of new-technology solar cells, along with the procedures needed to eliminate or passivate these mechanisms. The development of sophisticated material and cell evaluation techniques in the tests and measurements activity is aimed at establishing and measuring critical material and cell parameters that can influence cell performance. The technical issues area addresses topics such as environment, health and safety effects, materials availability, economic analysis, and the definition of systems requirements for advanced photovoltaic technologies.

Technology Development

Technology development objectives are to develop technically feasible, low-cost candidate photovoltaic component and subsystem technologies to the point where technology readiness can be demonstrated. The strategy is to pursue technology options that continue to show promise of meeting the program goals, thereby increasing the probability that at least one technology will be successful.

A subprogram includes the technology development of photovoltaic array components and modules for flat-plate and concentrator designs and the technology development of balance-of-system (BOS) components based on the requirements established by the system engineering group. The latter includes array structures, power conditioning, power controls, protection, and storage.

Flat-Plate Solar Arrays

Obstacles to the large-scale manufacture of solar cells and modules are being attacked on every level. The photovoltaic materials, processes, methods of production, and transparent encapsulants and the final module, complete with cells and electrical contacts, are all undergoing intense development. In the United States the current focus is on conventional crystalline silicon. Concurrently silicon ribbon and a variety of thin film materials—such as CdS, amorphous silicon, and other compound semiconductors—are also being investigated in research and development laboratories.

The Jet Propulsion Laboratory is managing the Department of Energy's Low-Cost Solar Array (LSA) project. This project is developing a variety of solar cell types made from both silicon single crystals and silicon ribbon to meet the 1982 and 1986 collector cost targets. The operating premise is that the well-understood and advanced silicon technology has the best probability of becoming cost effective in the short term (by 1986). Research and development continues in other areas, such as thin-film photovoltaics. Five tasks have been identified in the LSA project, with each task aimed at reducing one segment of the overall cost of photovoltaic conversion. These tasks include the production of polysilicon raw materials, the formation of flat solar cell blanks (sliced ingot wafers, grown ribbons, or silicon sheets), cell encapsulation and module fabrication, cell fabrication and automated manufacturing, and large-scale production. Figure 2 displays the LSA project master plan for accomplishing program objectives.

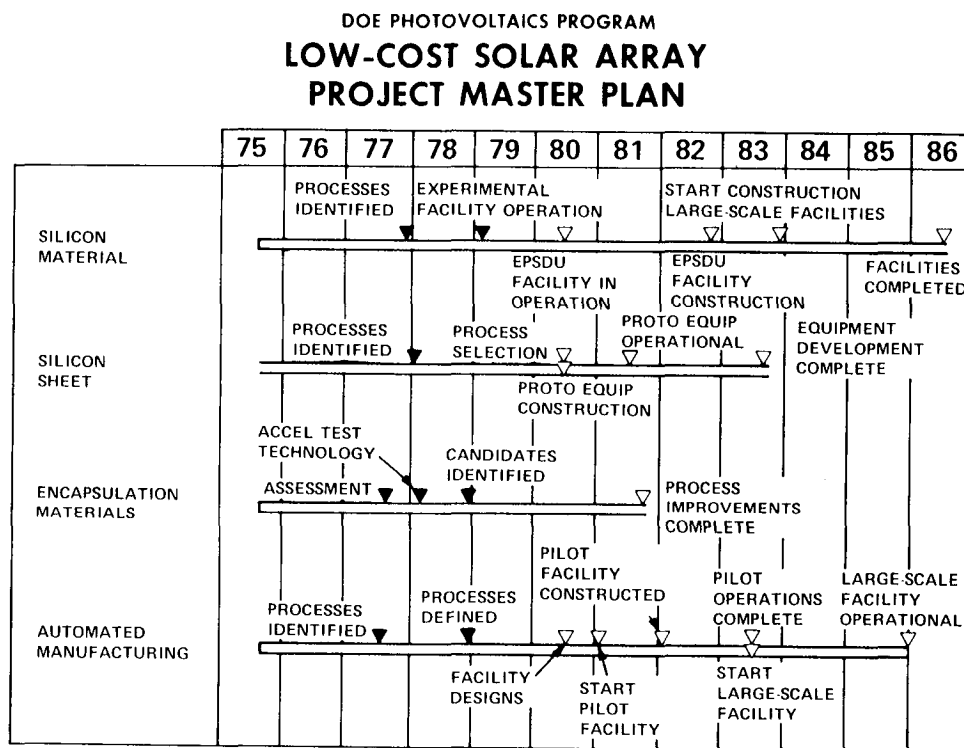


Figure 2

Reducing the cost of polysilicon is considered a crucial link in the production chain. Semiconductor grade (99.99999 percent pure) polysilicon, the feedstock for today's solar cells, now sells for \$60 to \$100 per kilogram. DOE hopes to cut that cost to \$14 per kilogram (in 1980 dollars) by 1986 and, possibly at the same time, determine if less pure solar-grade polysilicon could be used to make cheaper cells with acceptable performance. With these prices and availability in mind, funding has been provided for four low-cost-polysilicon production processes being developed by U.S. companies. To develop a better understanding of the feasibility of using solar-grade polysilicon for cells, contractors are investigating the trade-offs between purity and cell performance.

The project is also working to reduce the cost of transforming purified polysilicon into large sheets of single-crystal material suitable for cell fabrication. This step has great potential for cost reduction—from about \$5.80 per W_p in 1976 to \$0.21 per W_p by 1986. Several different processes are also being funded that yield single-crystal silicon in one of three forms: ingots, shaped ribbons, or sheets.

Unlike solar cells used on spacecraft, terrestrial photovoltaics must survive sunlight, moisture, salt spray, animals, vandals, ice, and snow. The objective of the third task is to develop a low-cost module encapsulation system that can be expected to last for at least 20 years. Nine contractors are now working on encapsulants.

The final step in producing a solar cell is its conversion from wafer, ribbon, or film into a finished multicell module that is ready for installation. This process represents about 65 percent of the cost of a finished module. In 1976 this was about \$15.40 per W_p . Based on studies of mass production techniques, we believe that finished modules can be reduced to less than \$0.70 per W_p by 1986, if plants are built that produce at least 25 megawatts of cells annually. The project therefore aims to identify, develop, and demonstrate the feasibility of those processes that can be automated and incorporated into a mass-production sequence.

Concentrator Collector Technology Development Objectives

Because the primary limitation to photovoltaic conversion is currently the high cost, another approach is the use of concentrator optical systems that focus sunlight onto solar cells. Here, since the area of the cell is only a small portion of the collector area, the cell cost contribution is significantly smaller. The cost of the array then depends on the concentrator cost, the cost of the support structure, and the tracking mechanisms.

The development of a low-cost, concentrator collector is the responsibility of Sandia Laboratories, Albuquerque, New Mexico. The Concentrator Technology Development project objectives include the development and evaluation of solar concentrator system components, materials, and manufacturing processes leading to low-cost solar concentrator collectors for photovoltaic conversion. Stimulation of commercial availability is inherently part of the objectives. The project has three major tasks: solar concentrators, concentrator-enhanced subsystems, and concentrator cell technology. Figure 3 displays the Concentrator Technology Development master plan for accomplishing the objectives.

The concentrator-enhanced array subsystems task includes designing, optimizing, fabricating, testing, and evaluating full-sized arrays based on designs developed in the preceding task. The objectives of this task are to expose and solve problems associated with fabricating, testing, and operating full-sized, multikilowatt concentrating arrays. Procurement of these arrays will facilitate future array procurements by test and applications programs. Another important feature of this task is array testing and evaluation. Testing includes optical testing, accelerated lifetime testing, severe environment testing for array components and materials, and real-time continuous operation array testing to obtain performance data for the complete array subsystem over long periods of time.

The concentrator cell technology task is concerned with the development of silicon cells and advanced cells and conversion devices for use in concentrated sunlight. The objectives of this task are to investigate the performance potential of single-crystal silicon solar cells and compound semiconductor solar cells, such as single-crystal gallium-arsenide cells, under high illumination and at

DOE PHOTOVOLTAICS PROGRAM
CONCENTRATOR TECHNOLOGY
DEVELOPMENT PROJECT

ACTIVITY	FY						
	80	81	82	83	84	85	86
CELL DEVELOPMENT	20% CELLS PRODUCED ▼	DESIGN SELECTION ▼	RELIABILITY ASSESSMENT ▼		30% ADVANCED CELLS ▼		
		PREFERRED DESIGNS SELECTED ▼	HIGH CONCENTRATION MODULE DEMONSTRATED ▼		ADVANCED MANUFACTURING PROCESS ▼		
CONCENTRATOR DEVELOPMENT							
ARRAY SUBSYSTEM DEVELOPMENT	\$2.80/W _p DESIGNS ▼	\$0.70/W _p DESIGN ▼	15% ARRAY EFFICIENCY ▼			\$0.50/W _p DESIGN ▼	

Figure 3

high temperatures, to define cell structures and designs that optimize cell performance for various intensity and temperature conditions; to develop viable cell production methods; to establish commercial sources of reliable cells; and to develop new, high-performance conversion concepts.

System Performance Requirements

The major components of a photovoltaic system are shown in figure 4 and include

- (1) Collectors, including the solar photovoltaic conversion devices and their interconnections
- (2) Power conditioning equipment to convert direct current to alternating current and to provide regulated outputs of voltage and current
- (3) A processor-controller that automatically manages the operation of the total system
- (4) A storage system (if used) that stores excess energy during periods of high collector output for use during periods of low (or zero) output

The power conditioning, processor-controller, and storage subsystems, along with their interconnections, are lumped under the term "balance of system" and may be very similar, or even identical, for both flat-plate and concentrator collectors. Not mentioned were the support structures,

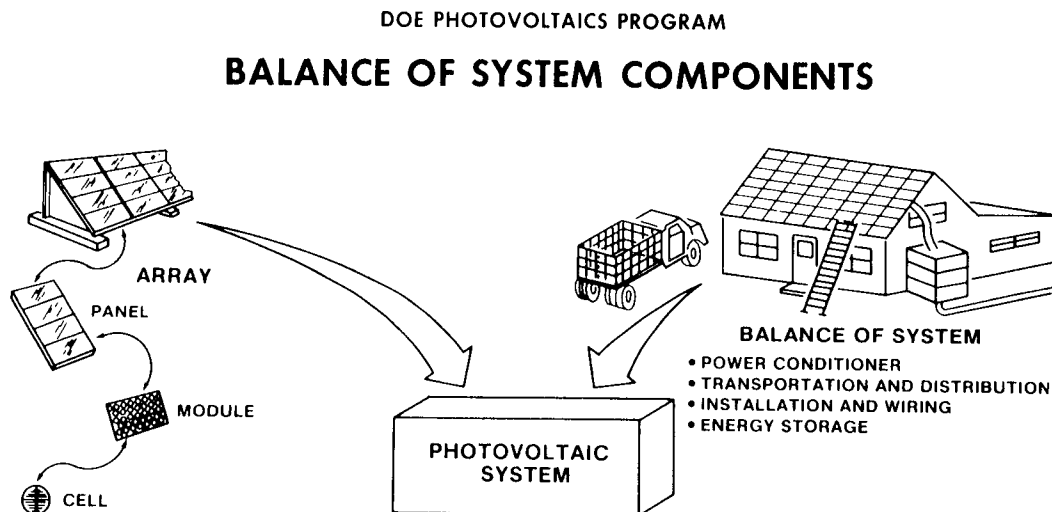


Figure 4

which are considered separately for flat-plate collectors but are usually an integral part of a concentrator collector. Because of the geometric optics involved, concentrator collectors are nearly always designed to provide tracking to maintain a high output throughout much of the solar day. Flat-plate collectors are usually mounted on fixed supports and have an output that varies approximately sinusoidally about solar noon.

The modularity of photovoltaic collectors permits a wide range of applications for these systems. As mentioned earlier the four types of applications presently considered viable are (1) stand-alone systems, primarily small power systems for remote applications; (2) residential systems; (3) intermediate-load centers; and (4) central stations. The last three systems are normally expected to be utility connected.

The performance requirements for a photovoltaic system are very similar to those for other electric power systems. They include low maintenance, high reliability, fail-safe capability, safety, and continual automatic operation that is responsive to the demands of the user, ensuring optimum use of the available energy.

Photovoltaic systems must maintain satisfactory output regardless of atmospheric environment, buildup of dust and dirt, and long exposure to possible corrosive materials. Mechanical damage from hail, high winds, and electrical storms can be minimized by proper design and choice of materials. The maintenance costs for cleaning and repair must be considered along with the initial installed system cost when choosing any photovoltaic installation.

Photovoltaics—Present and Future Applications

Each of the various field centers participating in the U.S. National Photovoltaics program focuses on a particular aspect of the ongoing tests and applications activities throughout the country. This also includes a measure of international activity, as summarized in table I.

Stand-Alone Applications

The NASA Lewis Research Center in Cleveland, Ohio, has the responsibility for the remote stand-alone applications sector. The objective is to develop photovoltaic systems that have the potential to be used in significant quantities in worldwide markets. An important part of this activity includes demonstrating these systems cooperatively with users in a way most likely to stimulate markets. Table II describes some of the completed tests and applications. During the next year and beyond, work will continue on additional international applications in the agricultural, cottage industry, health, and village power application areas. These systems will characteristically be modular, direct-current applications with battery storage; sizes will range from less than a kilowatt to 15 kilowatts.

The Massachusetts Institute of Technology and the Lincoln Laboratory (MIT/LL) have, in the past, conducted their activity in the stand-alone applications sector on larger alternating-current projects. Objectives were to establish the technical credibility of solar photovoltaic power systems, to identify and eliminate technical and institutional constraints that might inhibit widespread acceptance, to provide data for economic modeling, and to reinforce the goals of the National Photovoltaics program. Table III describes some of the completed tests and applications. MIT/LL has the responsibility for the residential applications sector and during the coming year and beyond will concentrate efforts on that sector, with the first residential system evaluation experiment expected to become operational in November 1980. Residential applications planned through 1986 include construction of several hundred photovoltaic residences in various geographic regions.

Intermediate-Load-Center Applications

The Sandia Laboratories in Albuquerque, New Mexico, is responsible for tests and applications in the intermediate-load-center applications sector. Their objectives parallel those of the residential

TABLE I.—U.S. DEPARTMENT OF ENERGY PHOTOVOLTAIC
TESTS AND APPLICATIONS

Responsible organization	Remarks
Sandia Laboratories Five concentrator and four flat-plate projects entering construction phase in seven states (2020 kW)	-----
MIT/Lincoln Laboratory 25-kW agricultural pump; Mead, Nebraska 100-kW power source; National Bridges National Monument, Utah 15-kW daytime broadcast radio station; Bryan, Ohio	Operational in 1977 Operational in March 1980 Operational in August 1979
Department of Defense 60-kW grid-connected radar station; Mt. Laguna, California	Operational in June 1979
Oak Ridge National Laboratory 240-kW power installation; Mississippi County Community College, Blytheville, Arkansas (trough concentrator technology) 200-kW power installation; Northwest Mississippi Junior College, Senatobia, Mississippi 500-kW power installation; Georgetown University, Washington, D.C.	Under construction Under construction In design
SERI 350-kW village power system, Saudi Arabia (Soleras) (Fresnel lens concentrator technology)	Contract announced October 1979
NASA Lewis Research Center 3.5-kW village power system; Papago Indian village Schuchuli, Arizona 1.8-kW village power system; Tangaye, Upper Volta 19 small stand-alone applications, less than 1 kW each	Operational in December 1978 Operational in March 1979 -----

applications, with emphasis on photovoltaic systems connected to the electric utility grid. In June 1979, twelve designs were selected for construction and operation by industry teams at locations throughout the United States. A total of 1.1 megawatts of these flat-plate and concentrating systems should be operational by the end of 1980. Industry teams will also design and conduct evaluation experiments on several other advanced systems in the megawatt range through 1986.

College Projects

The Oak Ridge National Laboratory (ORNL) is providing technical support to three college projects being designed and constructed under grants from DOE. These projects are

(1) A 240-kilowatt concentrating application, with active cooling and thermal utilization, at the Mississippi County Community College in Blytheville, Arkansas

(2) A 200-kilowatt testbed incorporating many photovoltaic technologies, as part of a total energy system, at the Northwest Mississippi Junior College in Senatobia, Mississippi

(3) A proposed 500-kilowatt exemplar project at Georgetown University, Washington, D.C.

The objective is to ensure that these grants projects derive maximum benefit from the ongoing photovoltaics program while experience is being gained in larger cogeneration energy systems.

International Applications

The Solar Energy Research Institute (SERI) is responsible for implementing a 350-kilowatt village photovoltaic power system near Riyadh, Saudi Arabia. The objective is to fulfill the terms of a

TABLE II.—NASA LEWIS RESEARCH CENTER

PHOTOVOLTAIC APPLICATIONS

Application	Service requirements	Operational period	Status
Refrigerator power (330 W) installed in July 1976	Medical and food supply storage at Papago Indian Village, Sil Nakya, Arizona	Continuous	In operation ↓
Forest lookouts (588 W) installed in October 1976	Power for water, lights, radio, and refrigerator at two forest lookouts in California	May to October	
Weather stations (481 W) installed in April-August 1977	NQAA weather station power supply at five locations in New York, Florida, New Mexico, Arkansas, and Hawaii	Continuous	
Highway dust warning sign (116 W) installed in April 1977	Power for receiver, transmitter, motor, and lights on changeable message sign near Tucson, Arizona	Continuous	
Water cooler (446 W) installed in July 1978	Demonstration photovoltaic powered water cooler for visitor center at Lone Pine, California	Continuous	
Refrigerator (220 W) installed in July 1978	Food storage for back country ranger station in wilderness area	Summers	
Village power (3500 W) installed in December 1978	Power supply for 95 people in Papago Indian village, Schuchuli, Arizona for water pump, 15 refrigerators, 47 lights, washing machine, and sewing machine	Continuous	↓

U.S.-Saudi bilateral agreement to foster alternative energy technology development and early demonstrations. This system will use Fresnel lens concentrating collectors.

Military Applications

The U.S. Army Mobility Equipment Research and Development Center, headquartered at Fort Belvoir, Virginia, participates in a joint Department of Defense/DOE solar energy research program and is responsible for the development of photovoltaic systems for the U.S. Armed Services. In this program military demonstration projects have been conducted using photovoltaics in remote instrumentation, a radar station, a telephone communication center, battery charging, and a remote water purification system. These systems ranged from 35 watts to 10 kilowatts. During August 1979 a 60-kilowatt system was dedicated that augments a 600-kilowatt diesel-powered grid at the Mt. Laguna Air Force Station, near San Diego, California.

TABLE III.—PHOTOVOLTAIC FIELD TESTS CONDUCTED BY
MIT AND LINCOLN LABORATORY

Application	Size, kW _p	Location	Status
Agricultural test facility; large- and small-scale irrigation, crop drying, fertilizer manufacturing, etc.	25	Mead, Nebraska	Operational since July 1977
Public education (electric power for museum exhibit)	1.6	Chicago, Illinois	Operational since August 1977
Lincoln Laboratory Photo- voltaic Systems Test Facility (test prototype residential system)	25	Lexington, Massachusetts	Installed in fall of 1979
Prototype photovoltaic load center system with stand- alone capability	100	Natural Bridges National Monu- ment, Utah	Operational since May 1980
Power for radio broadcast station	20	Bryan, Ohio	Operational since August 1979

Central-Station Applications

Initial planning envisions four central-station system applications tests during the 1983–1986 period, each expected to be 2 megawatts in size. The objectives of these experiments will include technical verification as well as obtaining operating experience in a utility environment.

Conclusions

Current technology development projections indicate that both flat-plate and concentrator photovoltaic collectors are expected to meet the established 1986 collector cost goals. As a result it is expected that a variety of collectors using both the concentrator and flat-plate approaches will be commercially available for application, both in the United States and in the international marketplace.

The future commercial potential of both flat-plate and concentrator technologies will depend on the economics of each application, with broad applications potential foreseen for both technologies. There are some applications well served by both, other major applications best served by flat-plate collectors, and others likely to be best served by concentrator collectors.

Solar Photovoltaics—Stand-Alone Applications

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Lewis Research Center
Cleveland, Ohio*

The Lewis Research Center has been involved in space photovoltaic research and development activities since about 1963. About 1970, we began to look at the feasibility of using photovoltaics for terrestrial applications and worked with a number of small experiments in the early 1970's. Then in 1975 we entered into the National Photovoltaics program described earlier by Dr. Ferber. The program started with the National Science Foundation, was transferred to the Energy Research and Development Administration and then later to the Department of Energy (DOE). About 1977 we entered into an agreement with the Agency for International Development (AID) to carry out a project in Upper Volta, West Africa. This project and other activities of the AID program are described in this paper in addition to our work for DOE.

For DOE, Lewis' role is the Stand-Alone Applications project. "Stand alone" means applications that are not associated with a utility grid or with central power. They are applications in which the normal source of power may be a diesel generator, batteries, or other types of power not connected to a utility grid. Our purpose is to accelerate penetration of photovoltaic systems in both near-term and intermediate markets for these applications and to work especially in the international sector. In that

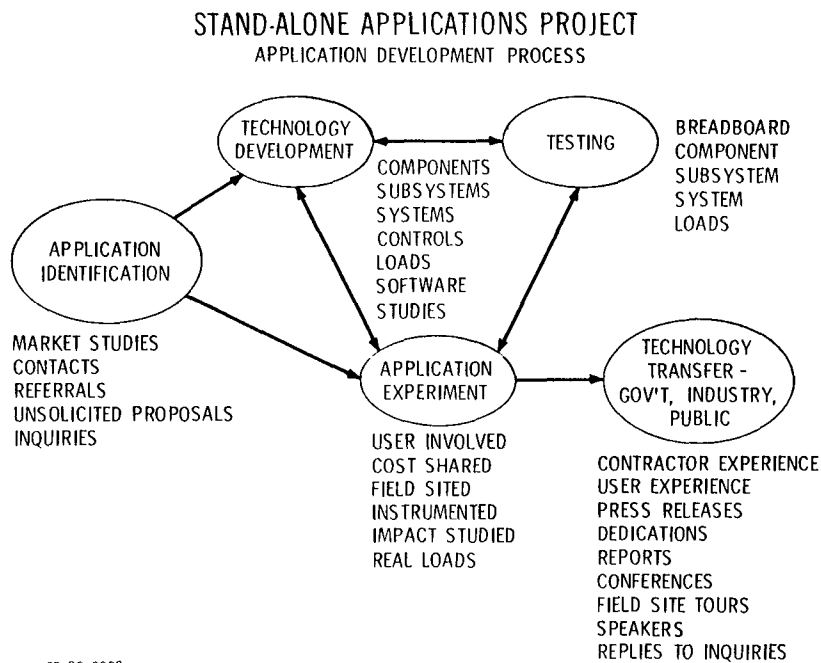


Figure 1

sector we are working primarily with developing countries. These countries represent the first major market for photovoltaic applications at this time.

Lewis' activities involve both development and implementation of applications as well as development of the technology for systems, subsystems, and components as needed. Figure 1 describes the process that is involved. The process begins when an application is identified by any of the methods shown. We then determine what technology developments are needed to carry out that application. We also begin to define an experiment that can be developed to demonstrate the application. In our experiments we always involve a user. That user participates in the cost and provides a site for the experiment that is part of the user's operation. We instrument the experiment to gain as much information as possible and of course study the effects of the application. We also conduct testing at all levels here at the Center to ensure that, when systems begin operation in the field, they will work as well as we can reasonably expect. And of course the purpose of all this activity is not to keep the information here, but to transfer it to industry, to the public, to other Government agencies, and to people who will make use of it and apply photovoltaics in other applications. This conference is one example of how we transfer this information.

Figure 2 shows the Lewis photovoltaic system test facility. Presently there are about 30 kilowatts of solar cells installed in this facility. In it we can breadboard systems and determine their characteristics, their interactions, and how they are going to operate before they go to the field.

Lewis has worked with quite a variety of applications over the last 5 years. Table I lists the smaller applications Lewis has fielded in which the power was used for a single purpose. The variety of categories shown includes instruments, communications, refrigeration, and highway. In all cases we have worked with a user such as the Coast Guard, the National Park Service, the Department of

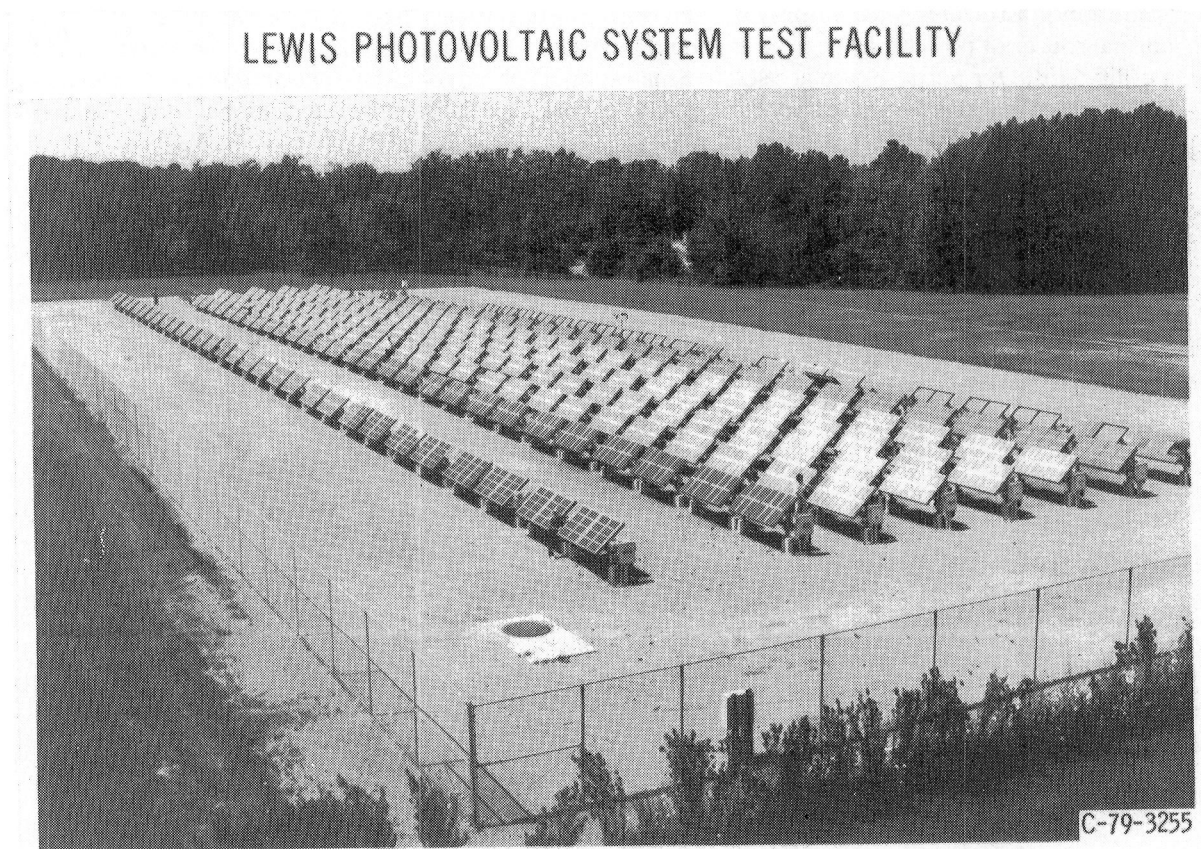


Figure 2

TABLE I.—LEWIS SINGLE PHOTOVOLTAIC APPLICATIONS

Application category	Use	User	Date operational	Location	Power level, W _p
Instrument	Weather data	USCG	Dec. 1972	Cleveland, Ohio	30
Instrument	Weather data	NOAA	Aug. 1973	Mammoth Mountain, California	60
Communications	Radio repeater	USFS	July 1974	White Mountain, California	16
Communications	Educational television	Govt. of India	July 1976	(1) Ahmedabad, India (2) Sambalpur, India	55 55
Refrigeration	Food preservation	USNPS	June 1976	Isle Royale, Michigan	220
Refrigeration	Medical	Village residents	July 1976	Sil Nakya, Arizona (Papago Tribe)	330
Instrument	Weather data	NOAA	Apr.-Sept. 1977	(1) New Mexico (2) New York (3) Hawaii (4) Alaska (5) Maine (6) Florida	75-150
Highway	Dust storm warning sign	DOT-AZ	Apr. 1977	Casa Grande, Arizona	116
Instrument	Insect survey traps	USDA	May 1977	College Station, Texas	23, 163
Refrigeration	Water cooler	Interagency visitor center	Oct. 1977	Lone Pine, California	446
Instrument	Air pollution monitor	NJ-DEP	Nov. 1979	Liberty Park, New Jersey	360
Instrument	Seismic monitors	USGS	Jan. 1980	Kilauea Volcano, Hawaii	18, 18

Transportation, the State of Arizona, and the Department of Agriculture. Many of these experiments date back a number of years. Locations and power levels for these experiments are also shown.

Table II lists cluster applications Lewis has fielded. These are applications in which the power is used for a number of purposes rather than a single purpose. The largest system—3500 watts—is the village power system at Schuchuli, Arizona. This is the largest application that Lewis has dealt with up to now. The final application listed was developed in cooperation with AID. It is installed in Upper Volta, West Africa, and has a power level of 1800 watts.

Figure 3 shows the experiment that Lewis did with the Government of India. Here we provided a small array of about 100 watts, with batteries housed beneath the array, to power a television receiver that was set up with an antenna to receive signals from the NASA ATS-6 satellite. This experiment was used to demonstrate the feasibility of using a satellite combined with solar energy to provide education to rural communities that are without electric power in countries such as India. The system performed quite satisfactorily.

Figure 4 illustrates an application involving a small portable array, about 220 watts, coupled to a standard 4.5-cubic-foot recreational vehicle refrigerator. In the base are six automobile batteries to provide power for operating the refrigerator at night. The box on the top provides instrumentation and some of the control functions. This system has operated satisfactorily at Isle Royale National Park during the summer seasons since 1976.

TABLE II.—LEWIS CLUSTER PHOTOVOLTAIC APPLICATIONS

Application category	Use	User	Date operational	Location	Power level, W_p
Fire lookout	Two-way radio, refrigerator, lighting, potable water	USFS	Oct. 1976	(1) Pilot Peak, California (2) Antelope Peak, California	294 294
Village power	Potable water, lighting, refrigerator, washing machine, sewing machine	Village residents	Dec. 1978	Schuchuli, Arizona (Papago Tribe)	3500
Village power	Potable water, grain milling	Village residents	Feb. 1979	Tangaye, Upper Volta	1800

PHOTOVOLTAIC-SATELLITE INSTRUCTIONAL TELEVISION EXPERIMENT SAMBALPUR, INDIA

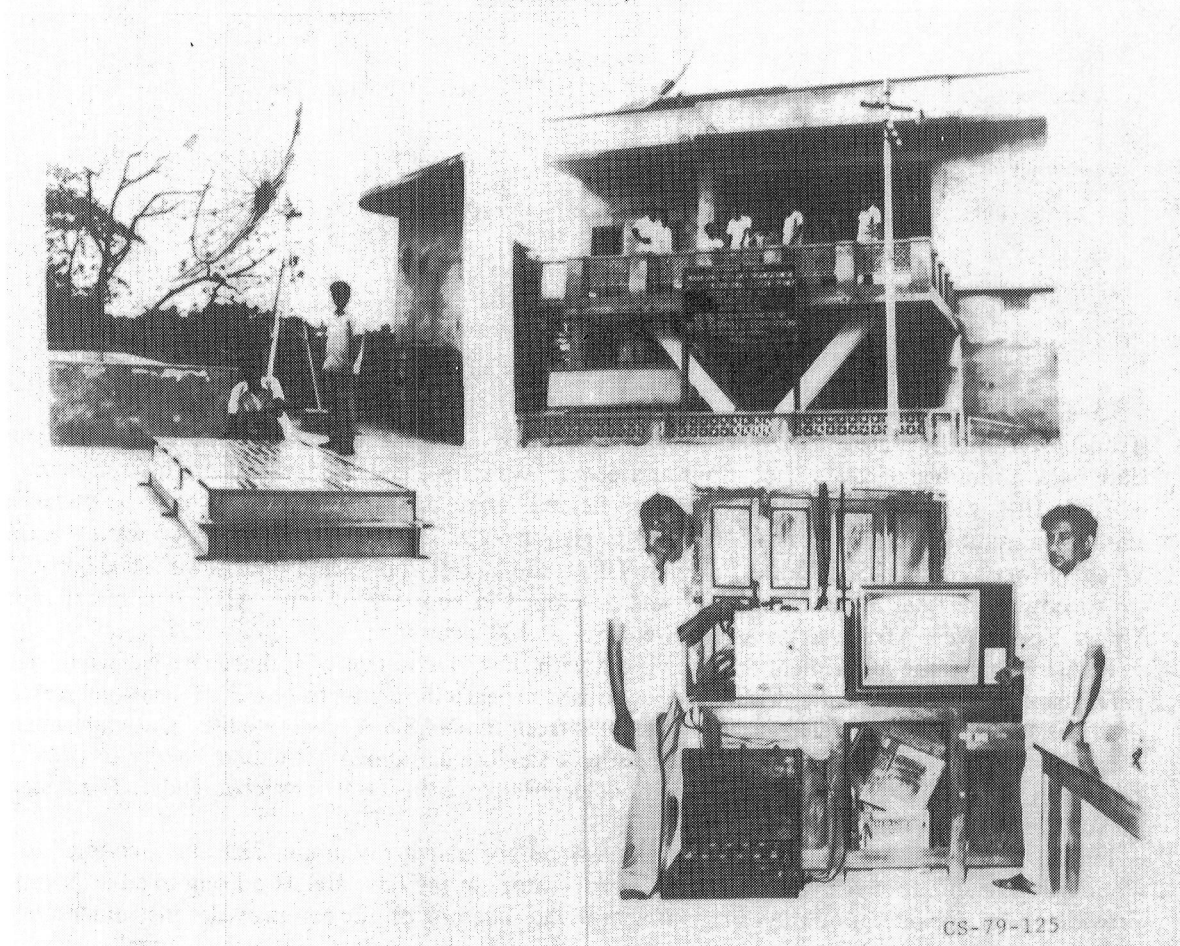
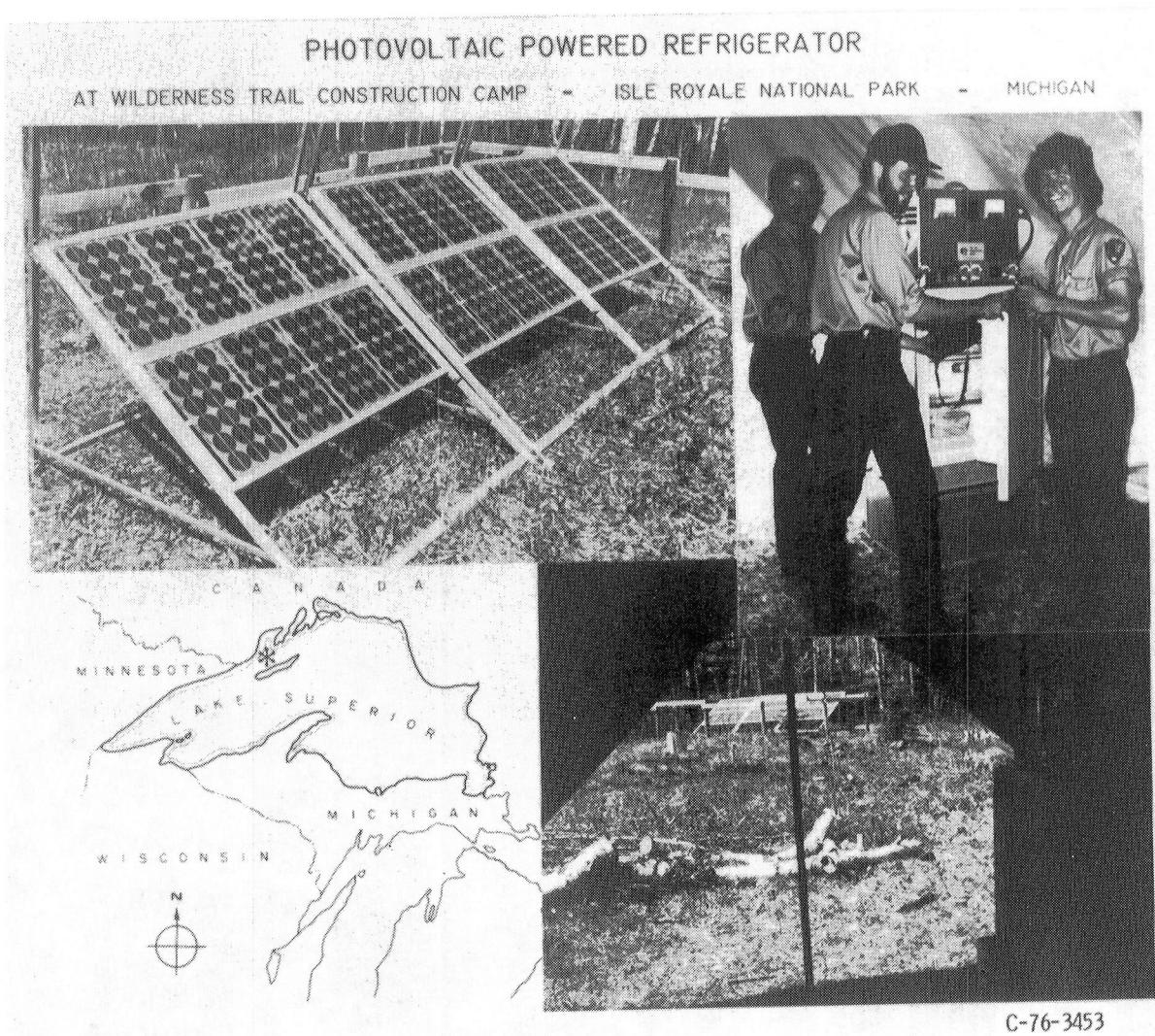


Figure 3



C-76-3453

Figure 4

Figure 5 depicts an application developed in cooperation with the Department of Transportation, State of Arizona. Arizona operates 40 of these dust storm warning signs along Interstate 10 between Phoenix and Tucson. We selected one of the signs and substituted the photovoltaic array and battery system for the existing power system to provide power for the sign. The power of the array is about 116 watts. The array provides power to rotate the sign, to operate the radio communication link that activates the sign, and to activate the lights mounted on the sign.

Another application category, shown in figure 6, involves remote weather stations operated by the National Weather Service. Here Lewis has provided a small array to operate the weather instruments and also to power the data communication link that transmits the data back to the National Weather Service Headquarters. This weather station is off the coast of Maine. We have installed similar systems at five other locations, including one each in Alaska, Florida, New York, Hawaii, and New Mexico.

With the Department of Agriculture, Lewis has provided some small arrays to power insect survey traps. These are shown in figure 7. The advantage of photovoltaics in this application is that it allows much more flexible siting of these insect survey traps. Normally researchers have to use a long extension cord to power these units from utility power. That becomes a little awkward when the

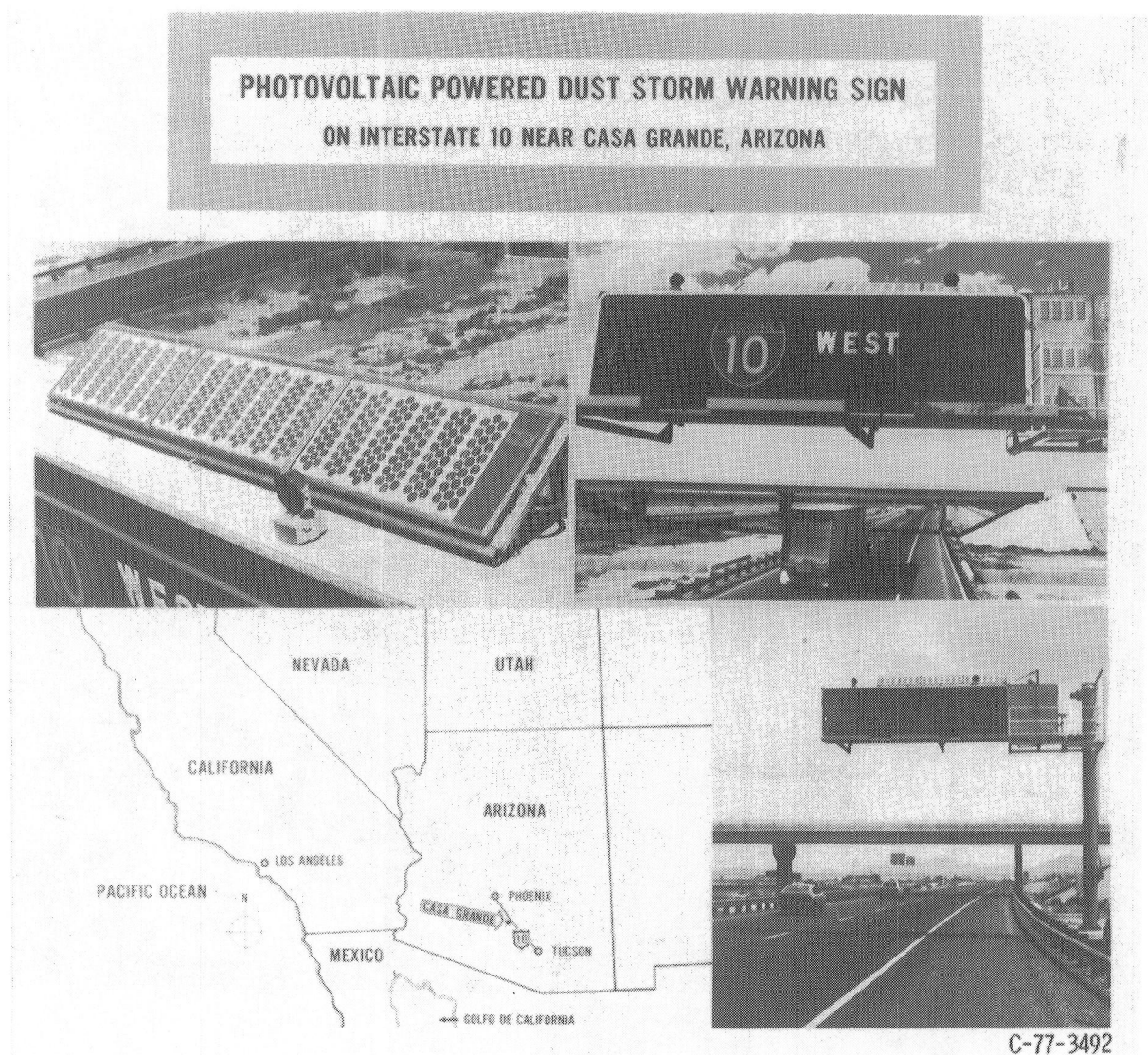


Figure 5

farmer plows the cord up with his tractor, and it also limits the locations where the traps can be placed. Photovoltaics has provided a flexibility that the agricultural people did not have before.

One of the cluster applications is shown in figure 8. This experiment was carried out with the National Forest Service. The application required a 300-watt array to provide power for operating the lookout. These lookouts are manned 24 hours a day throughout the fire season, which lasts about 6 months of the year year in this area. The power is used to operate, for the tower operator, a refrigerator, a small pump that pumps water to the sink in the cab from a holding tank in the base of the tower, two-way radio, and lights in the tower. These have been very satisfactory applications. They have been operating since 1977.

With the State of New Jersey, Department of Environmental Protection, Lewis has provided a 360-watt array to power a standard high-volume air sampler, as shown in figure 9. This air sampler is located at Liberty State Park in New Jersey, directly across from the Statue of Liberty. It is a new park that the State of New Jersey is developing. The design for this system provides both a display for the public and an operational system for powering the air sampler. With this setting we have the

PHOTOVOLTAIC-POWERED WEATHER STATION OFF COAST OF MAINE



Figure 6

opportunity to inform the public about photovoltaics, to show an example of what can be done, and to provide a source of power for a practical application.

The village of Schuchuli, Arizona, is shown in figure 10. This is a village of 95 people on the Papago Indian Reservation. It is 17 miles beyond the end of the electric power line. Here Lewis has installed a 3.5-kilowatt array. Power from the array is carried to the small building in the right foreground of the figure. This building houses the controls and batteries for the system. From that point part of the power is fed to an electric motor that drives the community water pump. The water is pumped into a large storage tank for village use. The balance of the power produced by the photovoltaic system is then distributed by pole line around the village and used for lighting, refrigeration, and washing and sewing machines, as shown in figure 11. All the appliances are direct-current (dc) powered, and the power is distributed as dc at 120 volts.

For AID, Lewis' activities have involved management of the Upper Volta project, mentioned earlier as an initial effort with AID. Since then the Center has been asked to manage the AID Photovoltaic Development and Support project. The purpose of this project is to demonstrate the suitability of photovoltaic technology to provide energy for development applications in countries that AID works with. The approach is to design, develop, and deploy these systems in a number of real settings. Some of the application categories involved are health delivery, communications, education, and water pumping.

Figure 12 shows the Upper Volta project. Upper Volta, located in the western part of Africa, is at the southern edge of the Sahara Desert. In the village of Tangaye, a photovoltaic system has been installed to provide power for pumping water and grinding grain. The photovoltaic array produces 1.8 kilowatts peak of power and is coupled to a lead-acid storage battery through a control panel that automatically controls and monitors the system. In addition to operating the water pump, located on top of the well, power is carried into the building to drive a grain mill. A light in that building is also powered by the array. This system has been in operation since March 1979 and is operating quite satisfactorily.

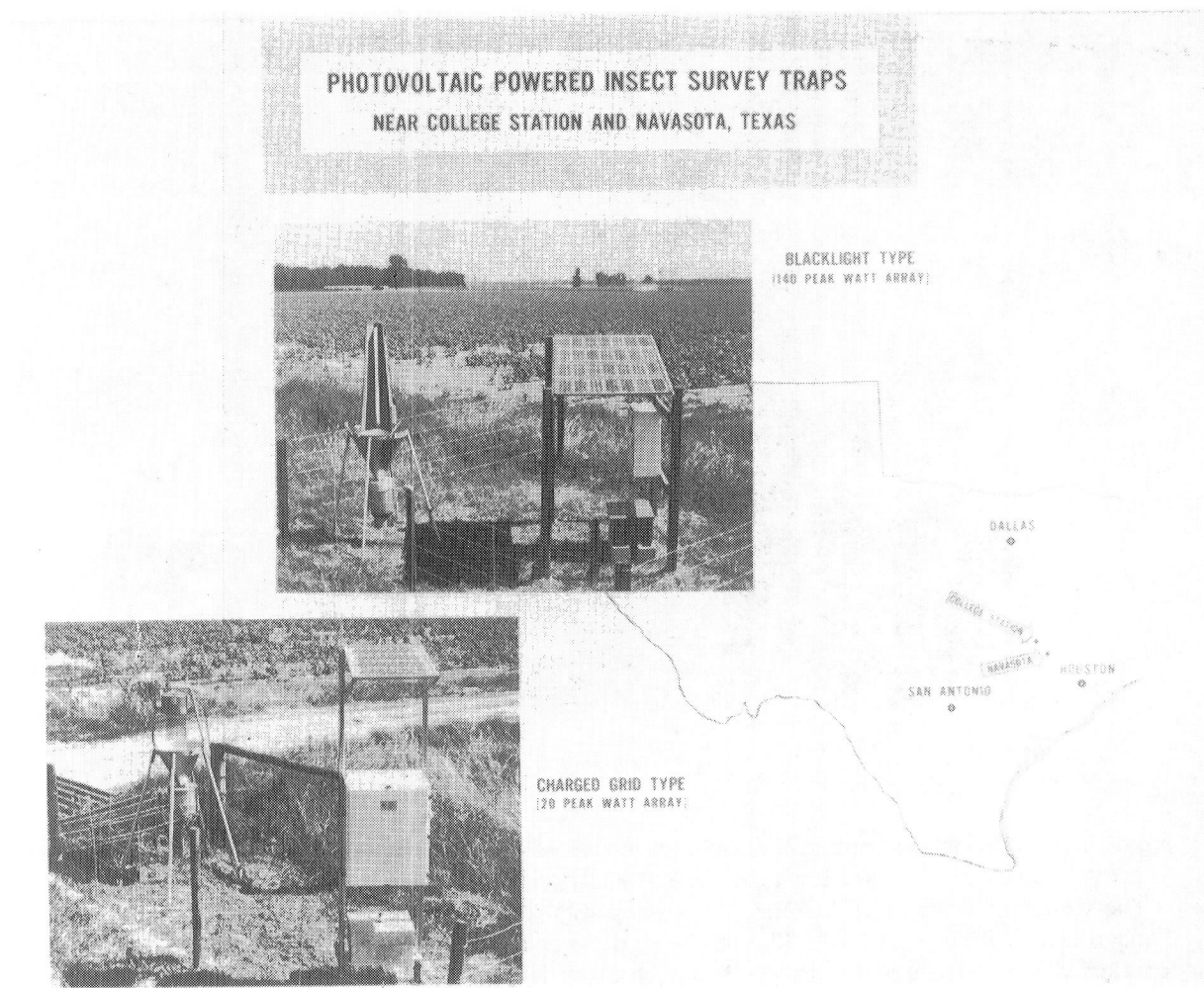


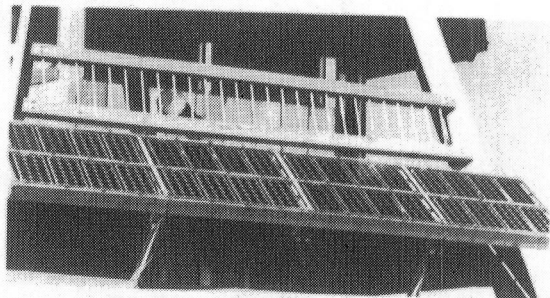
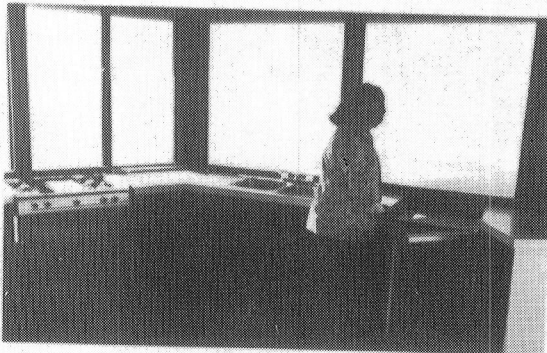
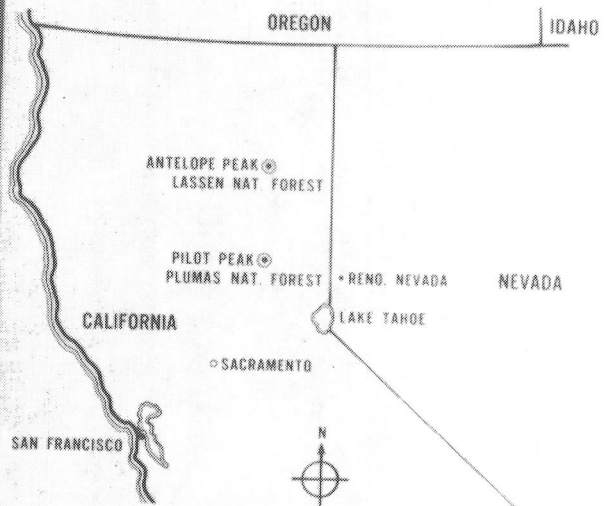
Figure 7

In conclusion, the development of photovoltaics has been proceeding for several years without much awareness by the public. But gradually more and more cost-effective applications are surfacing as the cost of photovoltaics comes down and the costs of other sources of energy go up. As these applications further develop and are noted in the news, the public will begin to realize the potential of photovoltaics. There are a lot of business opportunities developing—not just in making modules, but also in assembling systems. That area has not yet been penetrated very much by industry. The job of producing photovoltaic systems is a relatively straightforward engineering job. It involves providing batteries for storage (if the application requires it) electronic or electrical controls, wiring, connectors, enclosures, and the mechanical structure to support the array. These are tasks that many companies can readily adopt.

One example showing that some commercial interests are watching this technology carefully and are beginning to become involved with it is the case of Sears Roebuck. In Sears 1980 farm catalog you can buy a photovoltaic-powered electric fence charger. When a company such as Sears adopts a new technology, you know it must have some commercial potential to it.

PHOTOVOLTAIC POWERED FOREST LOOKOUTS

LASSEN AND PLUMAS NATIONAL FORESTS, CALIFORNIA



C-76-4766

Figure 8

PHOTOVOLTAIC-POWERED AIR SAMPLER
LIBERTY PARK, NEW JERSEY



Figure 9

3.5-KILOWATT PHOTOVOLTAIC VILLAGE POWER SYSTEM
SCHUCHULI, ARIZONA



Figure 10

PHOTOVOLTAIC-POWERED APPLIANCES AT SCHUCHULI, ARIZONA

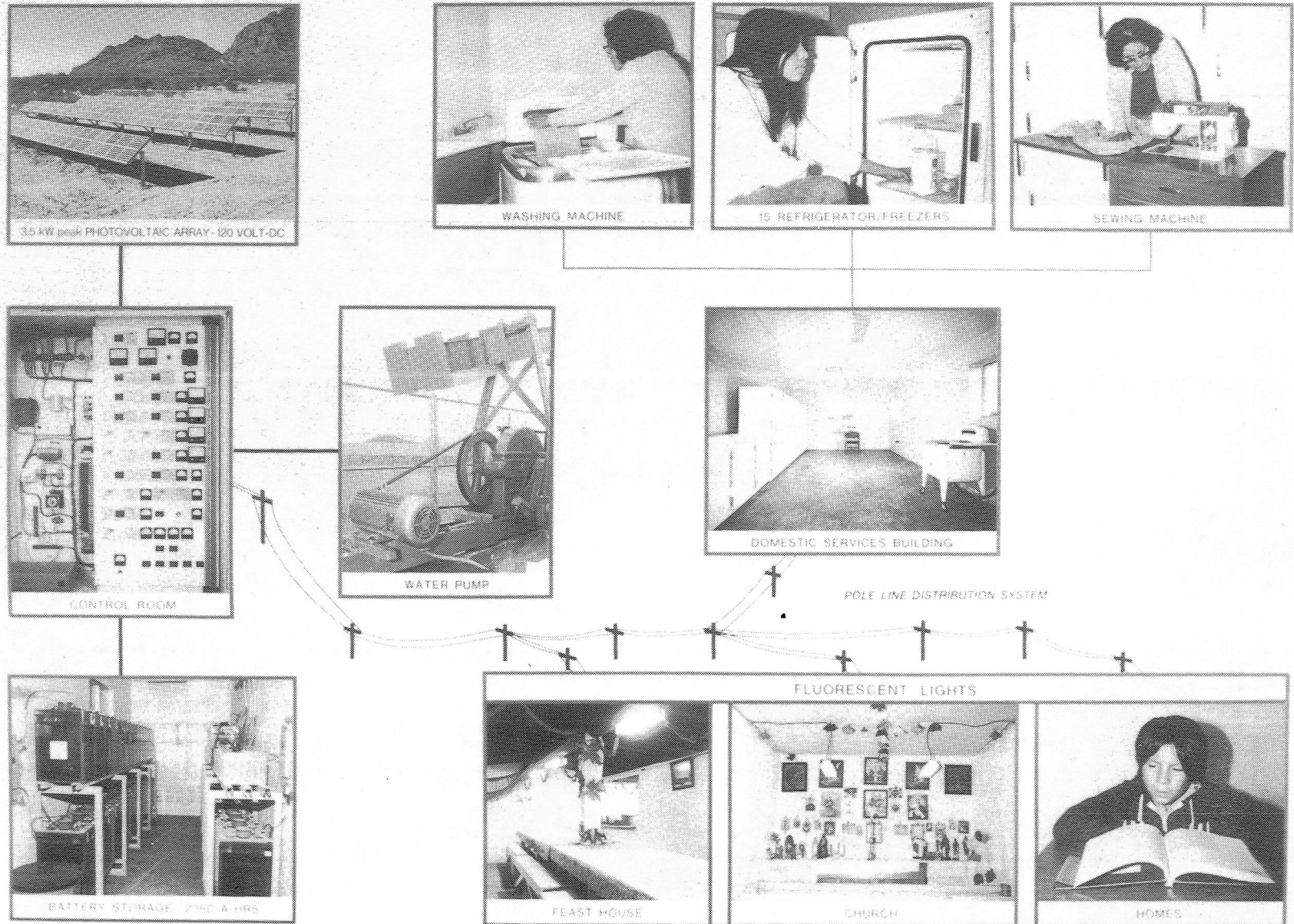


Figure 11

TANGAYE VILLAGE PHOTOVOLTAIC SYSTEM

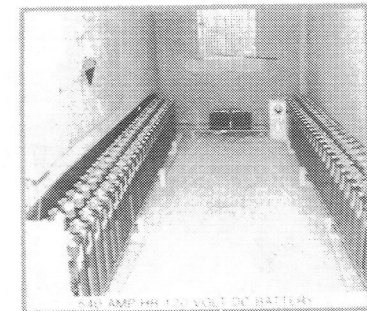
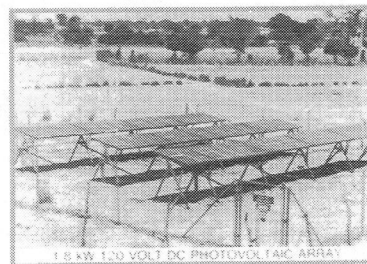
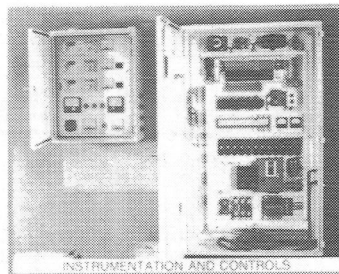
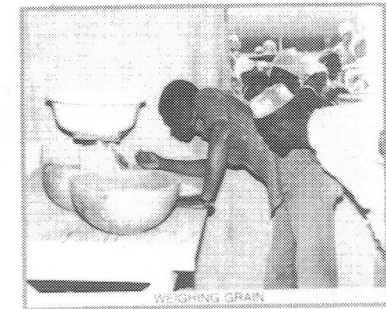
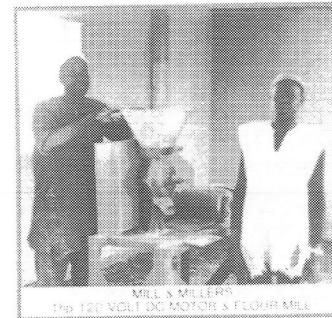


Figure 12

C-19-2511

Introduction to Materials Processing in Space

John S. Foster, Jr.*

TRW, Inc.

Cleveland, Ohio

This conference has been discussing ground-based energy and transportation both on the ground and in the atmosphere, areas in which we as a society have become dependent and areas which are also now highly industrialized. In the next paper, we are going to space. And we should recognize that, although we have been in space technology only a couple decades, we have already become quite dependent on it for information and knowledge. The information and knowledge come to us by means of communication satellites, weather satellites, reconnaissance satellites, and soon by navigation satellites. In addition, space technology is becoming industrialized.

Satellites have become indispensable servants for us in just a short time, and NASA is now experimenting with the possibility of manufacturing items in space and bringing back material that is unique because it has been processed in that unique environment. This idea of making special materials in the near zero-gravity environment of space has been a dream for more than a decade, and preliminary experiments were begun about 10 years ago. These were what you might call weightlessness experiments and were tried first on Apollo, then on Skylab, then on Apollo-Soyez, and more recently on small sounding rockets.

The preliminary results of the experiments are promising; they give indications that what people thought might happen seems to be happening. In order to undertake this kind of early research program on materials processing in space, NASA has, it seems to me, used a sensible approach, and done things in a balanced way. As a sometimes bureaucrat, I find that rather uncommon. In particular, it seems to me that the NASA approach in providing an opportunity for industry and universities and NASA in-house laboratories to work closely together from the outset on a common set of national pursuits is rather unique. NASA is also constructively using the peer review as a mechanism for assuring a sensible balance at the various phases of the program. I find the entire approach to be well structured and productive.

TRW, my organization, became committed in the 60's to an effort of pursuing the technology of materials processing in space. We would like to become an industrial user of space, and to do so we want to participate in the initial experimental stage. For the last 2 1/2 years we have been looking at the opportunities and have been functioning as a marriage broker between the NASA organization and a number of industrial organizations that have possible interests in using space for materials processing. TRW is also involved with TDRSS, the Tracking and Data Relay Satellite System for operation with Space Lab and the Shuttle, which will play an important role in future experiments.

*Vice President, Science and Technology, TRW, Inc.

Materials Processing in Space—Future Technology Trends

Neville J. Barter

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Redondo Beach, California

The United States National Aeronautics and Space Administration (NASA) is currently sponsoring a Materials Processing in Space (MPS) program. This program involves both ground and space-based research and looks to frequent and cost effective access to the space environment for necessary progress. The MPS program has its origins in research, but its eventual aim is directed at the utilization of space for product demonstrations and commercial ventures. Figure 1 calls out the four classes of materials research and indicates that demonstrations of space and ground-made products, from space processed material, are an integral part of the program.

NASA's goals and roles for the MPS program are shown in figure 2. The goals pertain to understanding, applying, and exploiting the microgravity of space to materials processing; the roles relate to the actions NASA intends to take for sponsorship of research, development of experimental equipment, and conduct of the pioneer steps to pave the way for industry/commercial initiatives.

The first generation payloads for research are under active design and development. They will be hosted by the Space Shuttle/Spacelab on Earth orbital flights in the early 1980's. These missions will focus on the acquisition of materials behavior research data, the potential enhancement of Earth-based technology, and the implementation of space-based processing for specialized, high-value materials. Some materials to be studied in these payloads may provide future breakthroughs for stronger alloys, ultrapure glasses, superior electronic components, and new or better chemicals.

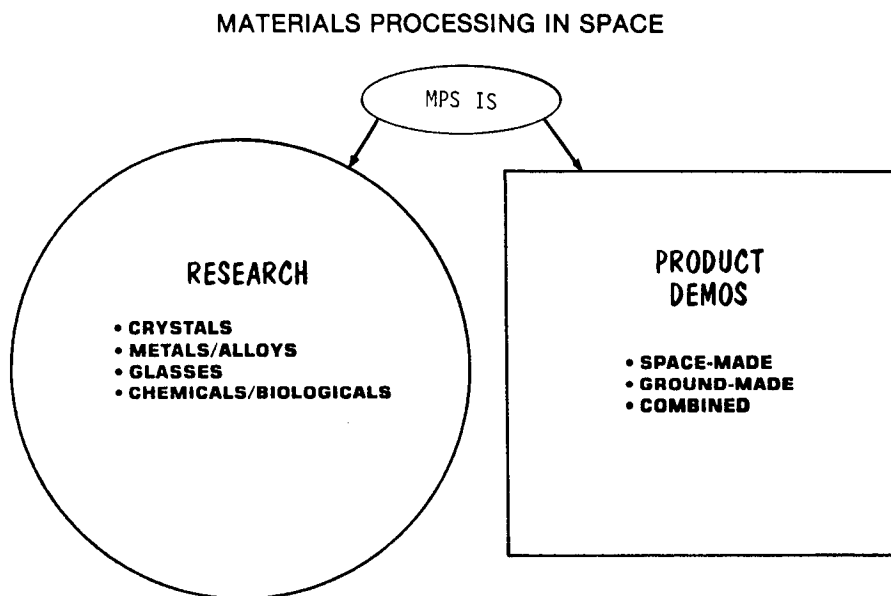


Figure 1

NASA' GOALS AND ROLES IN THE MPS PROGRAM

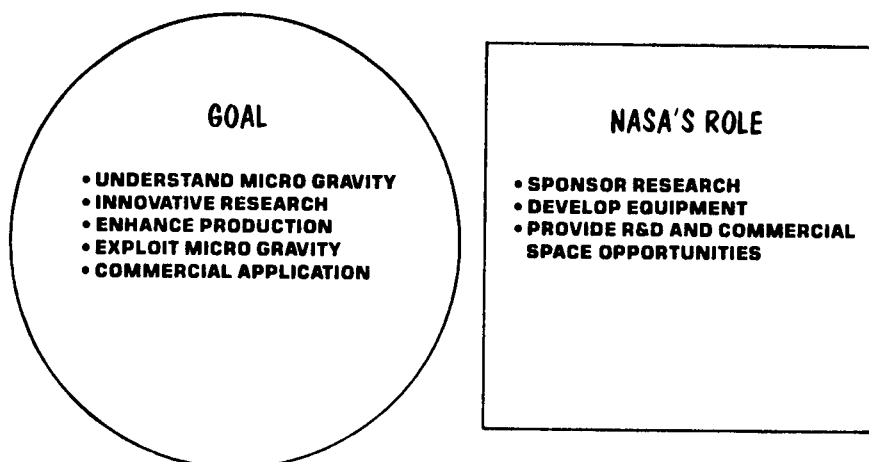


Figure 2

MPS Program Evolution

The Materials Processing in Space program has conducted approximately 70 flight experiments in space on Apollo, Skylab, ASTP, and Space Processing Applications Rocket (SPAR) flights (fig. 3). The results of these experiments demonstrated that the weightlessness of the space environment provides some dramatic effects on key phenomena involved in technologically important processes. This experimental work will be conducted on Space Shuttle flights starting as early as 1982 through the integration of SPAR experiment apparatus in the Materials Experiment Assembly (MEA).

The MPS program has initiated the MPS Spacelab Payloads Project. Currently three MPS payloads are being developed for flights on Space Shuttle missions in 1983. These payloads will be accommodated in the Spacelab module or on the Spacelab pallet.

Payload hardware is being designed to conduct solidification experiments using high temperature furnaces. To take advantage of the high power available due to the absence of the pressurized Spacelab module, this payload will be located on the pallet in the Shuttle bay.

A fluids experiment system and a vapor crystal growth experiment are also being developed. These experiments will be conducted with the aid of the payload specialist in the habitable environment of the Spacelab module.

The three Shuttle Spacelab MPS payloads are shown in their flight configuration in figure 4.

There are several other efforts under study for consideration as first-generation Shuttle/Spacelab hosted MPS payloads. They are the Polymer Latex Reactor, Acoustic Containerless, and Analytical Float Zone Systems.

The three first-generation payloads, now under hardware development, are described below.

Solidification Experiment System

The solidification experiment system (SES) is a Shuttle bay pallet-mounted payload which automatically melts, refines, and resolidifies a broad range of materials (fig. 5). It is a copassenger on a Shuttle mission with communication satellites which will be deployed early in the mission, allowing the SES payload to use all available electric power from the Shuttle's fuel cell to operate MPS experiments for the remainder of the 7-day Shuttle mission. The SES involves directional solidification, gradient freeze, and isothermal processing.

MPS EVOLUTION

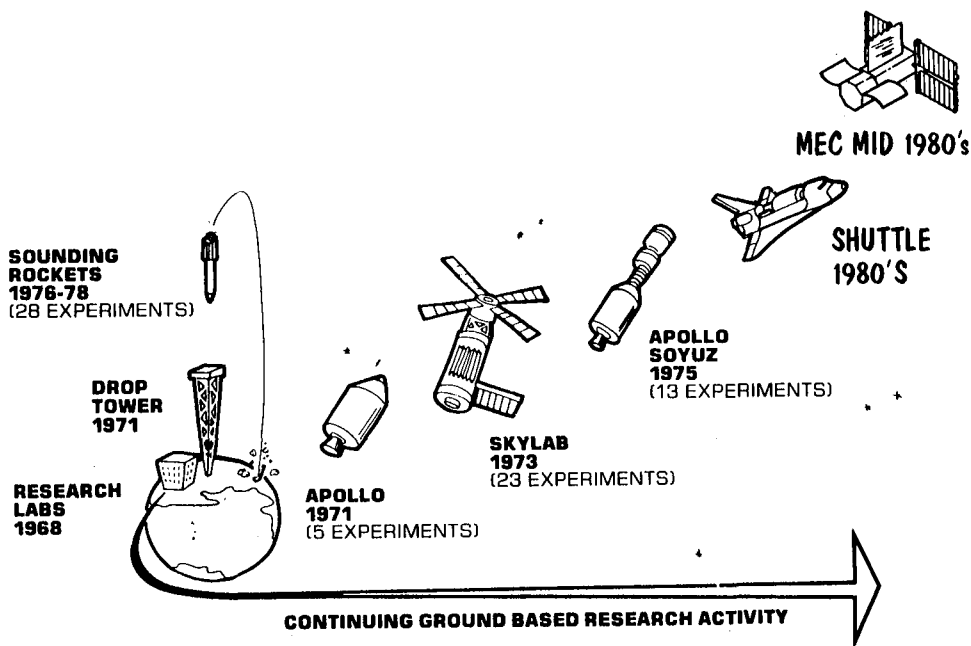


Figure 3

MPS/SPACELAB 1983 FLIGHTS

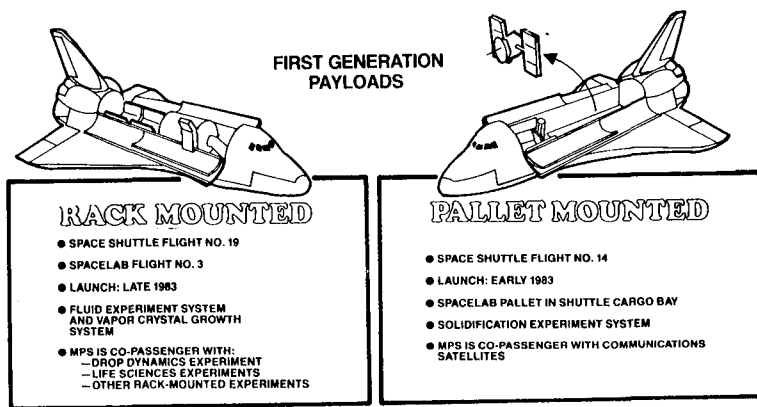


Figure 4

SOLIDIFICATION EXPERIMENT SYSTEM CONFIGURATION

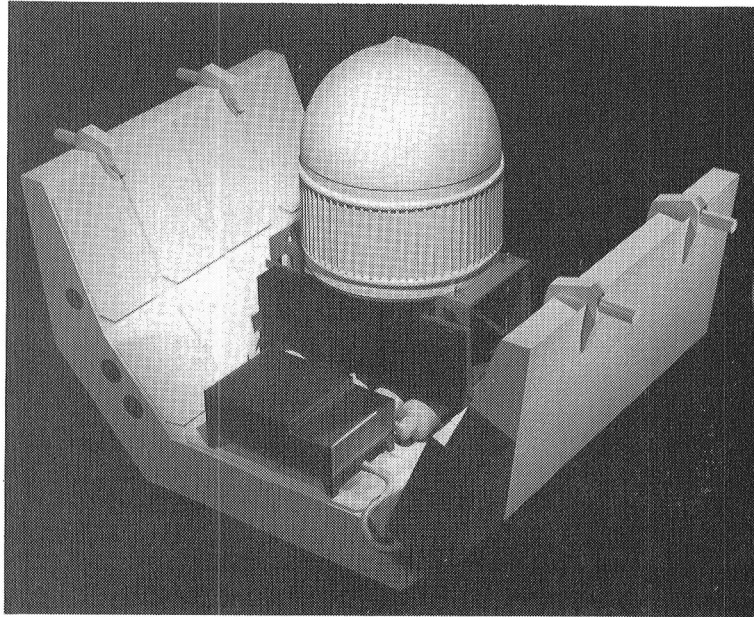


Figure 5

Directional solidification processing is designed for the production of highly uniform crystalline solids from a melt. A furnace for directional solidification processing must provide a uniformly high temperature environment in one end and a low temperature in the other end. A test specimen of the desired composition is inserted into the hot end, allowed to melt, and is then slowly withdrawn at a controlled rate. Crystal growth occurs at the solid-liquid interface which lies in the gradient zone, between the hot and cold ends. All SES experiments have as their goal the production of extremely uniform crystals of a degree of homogeneity which cannot be achieved in a terrestrial environment where the inevitable convection currents distort crystal growth.

Materials technology researchers have maintained a high level of interest in space solidification processing from the viewpoints both of the scientist desirous of using space as a new tool to study basic phenomena and of the materials engineer seeking to develop a commercial product which might benefit from a space environment in its manufacture. The objectives and investigative areas of solidification processing are given in figure 6.

There are four areas of study which will allow an assessment of the space environment for commercial solidification processing.

Geometry—because casting is a “net shape” process which provides objects in their final geometrical form.

Porosity—because castings must be sound (free from voids) and the absence of gravity alters traditional feeding mechanisms.

Nucleation—because natural convection, which plays a major role in crystal nucleation on Earth, is absent in space.

Dispersed nonmetallics—because they can represent either inclusions (which are deleterious), nuclei (which may or may not be beneficial) or a deliberately added dispersed phase, which opens a new class of materials: dispersion hardened solidification structures.

Gradients that can be achieved in a given test specimen will depend on the geometric and physical properties of the space specimen and on the properties of its container as well as on the thermal

characteristics of the furnace. One of the goals of experiment design will be to adjust hot and cold temperatures in the furnace so as to achieve a liquid-solid interface (at the melt temperature) which lies at a point of maximum gradient within the adiabatic zone. While these principles are common to all of the experiments, each also has its own peculiarities which must be considered in the experiment design.

Fluids and Vapor Crystal Growth Experiment System

A fluids experiment system (FES) and a vapor crystal growth (VCG) experiment system are also being developed to conduct crystal growth studies under weightless condition (fig. 7).

Crystals can be grown from fluids, from vapors, or from melts of solid materials. Payloads are planned to allow each of these phenomena to be investigated in Earth orbit. For growth from fluids (FES) there is an interchangeable experiment cell that allows crystals to be grown under controlled

SOLIDIFICATION STUDIES

OBJECTIVES

- SPACE AS A MANUFACTURING ENVIRONMENT
- SPACE PROCESSING APPLICATIONS TO EARTH SOLIDIFICATION PROBLEMS
- NEW MATERIALS

AREAS OF INVESTIGATION

- CASTING GEOMETRY
- CASTING POROSITY
- CRYSTAL NUCLEATION
- DISPERSED NON-METALLICS

Figure 6

FES/VCG CONFIGURATION

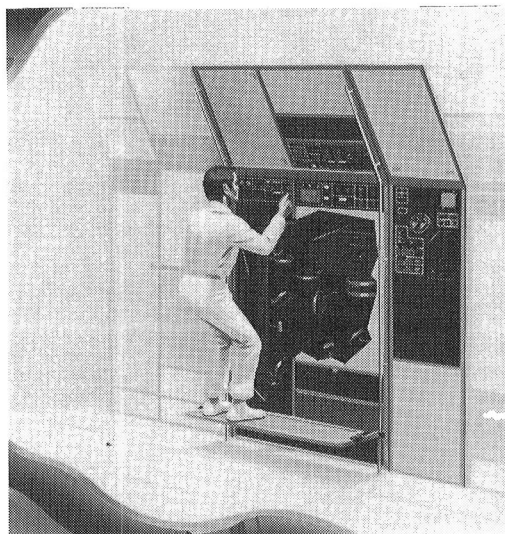


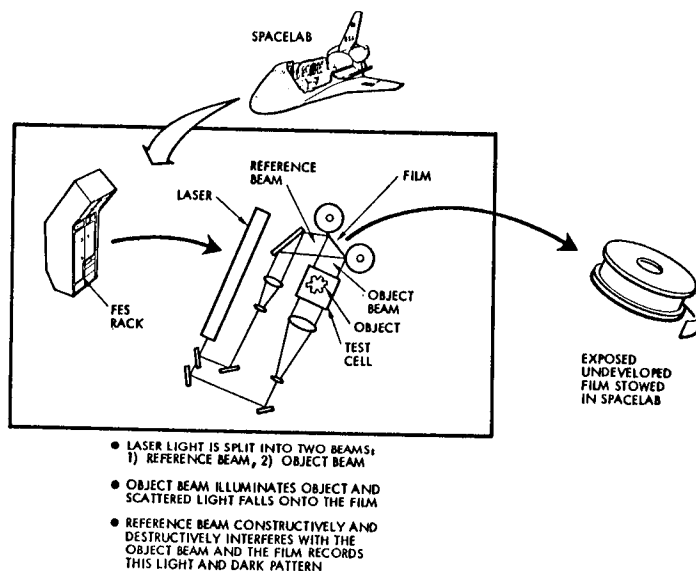
Figure 7

conditions while being observed by the on-board payload specialist and scientists on the ground. The cell is closely temperature controlled and has windows to permit halographic and video recording of the crystal as it is grown. Operation of the experiment is initiated by a payload specialist with seed crystal insertion. The halographic film and grown crystal are returned to Earth for data analysis.

The recording of holograms in-flight for the analysis of the Spacelab fluids experiment system allows the study of the in-flight image in a ground based analysis situation.

Figure 8 shows the essentials of the FES halographic system. The laser light is split into an object beam and a reference beam. The object beam illuminates the scene and then impinges on the film plane. The reference beam is a pure light beam that has the same path length as the object beam. The

THE FES HOLOGRAPHIC DATA SYSTEM IS MAJOR TECHNICAL CHALLENGE



OPERATIONAL MODE

- HOLOGRAPHIC SYSTEM FORMS PREPROGRAMMED DATA SEQUENCE OF EXPERIMENT EVENTS:
 - BOTH PARALLEL AND DIFFUSE LIGHT HOLOGRAMS GENERATED
 - TYPICALLY TWO VIEWS AVAILABLE EACH WITH A FILM TRANSPORT
- MANUAL OVERRIDE ALLOWS HOLOGRAMS TO BE MADE OF SIGNIFICANT EVENTS OUTSIDE PLANNED SEQUENCE
- SINGLE OR MULTI-EXPOSURE HOLOGRAMS CAN BE RECORDED
- UNDEVELOPED HOLOGRAMS ARE STOWED IN-FLIGHT AND DEVELOPED ON THE GROUND

CAPABILITY

- THE IMAGE CAN BE PROBED BY USING VARIED OPTICAL TOOLS:
 - MICROSCOPY CAN BE PERFORMED
 - INTERFEROMETRIC COMPARISONS BETWEEN SCENES CAN BE MADE
 - ALL IMAGES CAN BE RECORDED ON PERMANENT FILM
- GENERALIZED DATA THAT CAN BE OBTAINED INCLUDE:
 - CONCENTRATION GRADIENTS
 - TEMPERATURE GRADIENTS
 - PARTICLE MOVEMENT
 - BUBBLE MOVEMENT
 - FLOW PATTERNS
 - SOLIDIFICATION PATTERNS
 - INDEX OF REFRACTION CHANGES

Figure 8

two beams interfere at the film plane. The interference pattern contains all of the information that is in the object beam. There are two film transport locations. The total object beam falls on the forward film transport. Light scattered from the object falls on the transverse film. Both films contain the information regarding the object (i.e., crystal) such as changes in morphology and size.

All homograms made during a flight are stored in cassettes on board until landing.

Advanced Flight Systems

Currently in the definition stage is the materials experiment carrier (MEC) and its MPS payloads. The MEC is intended to fly attached to the NASA 25-kW power system on long missions starting in the mid-1980's. Figure 3 shows the MEC/25-kW power system as part of the MPS evolution.

Not shown in figure 3, but further along in the last decade of this century, the MPS program could feature large, manned modules fixed to a permanent materials processing, national space facility for large scale, commercial space processing.

Second Generation Payloads and Their Host Vehicles

The next major milestone for MPS payloads is anticipated in mid-1986. At this point the planned 25-kW power system is expected to become operational, and the projected needs of MPS in terms of numbers of samples, processing time, and power required to support sustained, systematic, MPS activity will exceed Shuttle capabilities. Thus the 25-kW power system capability and MPS needs can be matched. In operational terms the 25-kW power system provides the opportunity to (1) extend the orbital stay time of the Shuttle/Spacelab/pallet while providing a higher power level to the MPS payloads and (2) support experimental and commercial payloads while docked to the 25-kW power system as a free-flyer between Shuttle visits. Both of these capabilities provide significant benefits to the MPS program.

Previous analyses of the cost of performing research in space have shown that longer stay time, together with more power to run experiments, can dramatically reduce the unit cost of experimentation. Furthermore, ground-based research and flight experiments to date have shown that a significant number of samples must be processed in order to isolate, characterize, and develop MPS processes. In addition, the power requirements of MPS research and processing apparatus are typically higher than for other kinds of space activity. It is already apparent that the electrical power and energy resources of the Shuttle/Spacelab system will become a serious limiting factor to the MPS program at the levels of activity that are expected in the mid-1980's. The needs of the MPS program are as follows:

- (1) High electrical power energy
- (2) Long duration missions
- (3) Low g level during processing
- (4) Many samples processed per flight
- (5) Low cost per sample
- (6) Many reflight opportunities
- (7) Provisions for commercial proprietary endeavors

Consequently, the MPS program will become a primary user of the 25-kW power system since it offers increases in orbital stay time, electrical power, and in the free-flying mode microgravity stability at levels of 10^{-6} g or better. The 25-kW power system will be used by MPS in both the advanced Shuttle sortie mode and the free flying mode.

In the advanced Shuttle sortie mode (fig. 9) second and subsequent generation Spacelab Module MPS payloads that require manned participation will be accommodated. In this mode the Shuttle/Spacelab will dock with the 25-kW power system and support manned missions of up to 30 days. Payload planning showing payload growth is indicated in figure 10.

In the free-flying mode totally automated versions of the second generation MPS payloads will be

SHUTTLE BAY SORTIE MODE

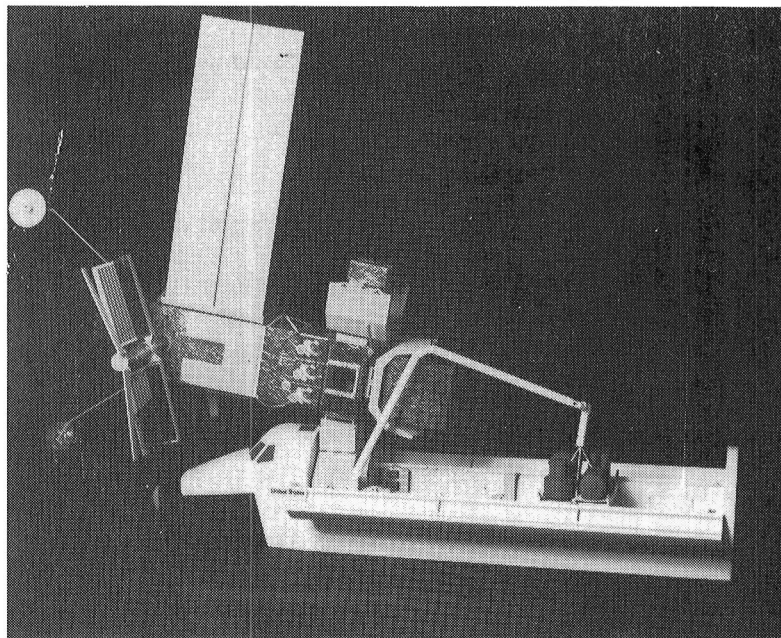


Figure 9

MPS PAYLOADS PLANNING

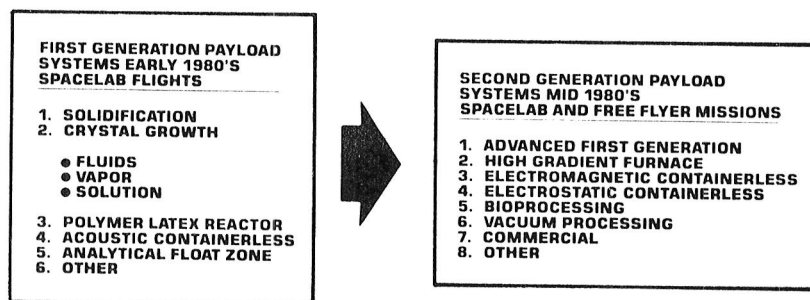


Figure 10

Space flight has opened a new environment in which the effects of gravity are essentially absent. We have only begun to understand or take advantage of this new promising phenomenon.

Space processing objectives are directed to the use of near zero gravity conditions which will prevail on Shuttle flights. The absence of significant gravitational effects over extended periods of time will give new insights into a number of materials processes and will offer a degree of process control not now feasible. We have achieved promising preliminary results on sounding rocket experiments which can provide zero-g environment for 5 or 6 minutes; in drop towers, which provide these conditions for a few seconds; and in experiments that were conducted during the Skylab program. The absence of significant gravitational acceleration suppresses settling sedimentation and buoyancy driven or natural thermal convection, which allows the enhanced control of temperature

fields. This permits production of crystals of increased compositional uniformity and also allows processing of materials in a containerless fashion (fig. 12).

The advantages to be gained by processing materials in space and the determination of what phenomena are important in controlling low-g processes must be understood. Previous space experiments on Apollo, Skylab, and SPAR demonstrated that natural convection arising from either thermal or concentration gradients could be adequately suppressed. Such flows are important because they give rise to nonuniform diffusion boundary layers as well as transient segregation due to temperature and velocity fluctuations during processes such as crystal growth (fig. 13). Indeed, it was demonstrated that crystals with fewer defects and with uniform composition, both on a micro as well as a macro scale, could be grown by taking advantage of the quiescent growth conditions in space. There are, however, other nongravitational flows, such as those induced by surface-tension

MEC MISSION OPERATIONAL ELEMENTS

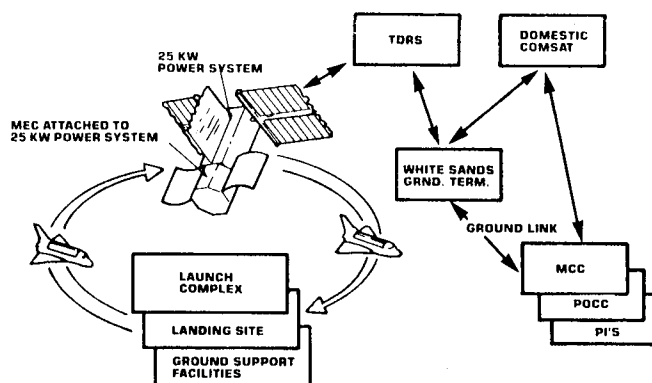


Figure 11

WHY SPACE?

THE MICRO-GRAVITY ENVIRONMENT OF SPACE GREATLY REDUCES PROBLEMS OF GRAVITY DRIVEN:

- BUOYANCY DRIVEN CONVECTION *
- SEDIMENTATION AND BUOYANCY SEPARATION *
- HYDROSTATIC PRESSURE
- CONTAINER EFFECTS

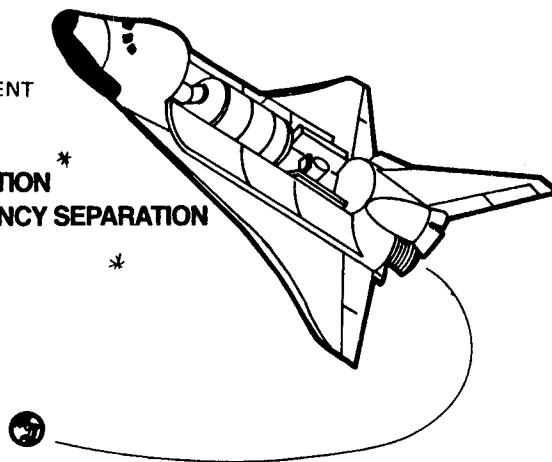


Figure 12

gradients, volume change, or spacecraft (laboratory) motion, that operate in space as well as on Earth. Such flows are often masked by gravity-driven convection and are difficult to study. Experiments in space provide a means of separating gravity-driven from nongravity-driven flows and studying them separately. This information is fundamental to the design of space experiments and processes. Additionally, many terrestrial processes may be improved by a better understanding of flows from which better control strategies can be devised.

The ability to handle liquids and melts in a containerless mode offers unique opportunities to perform a number of scientific experiments (determining thermodynamic properties of chemically active materials at high temperature, studying solidification at extreme undercooling, preparing ultrapure samples of material, and voiding container-induced nucleation of difficult-to-process, amorphous solids such as bulk metallic glasses and a variety of exotic glasses). Figure 14 shows the benefit and application of space processing to glasses and ceramics.

The elimination of sedimentation and Stokes flow in low gravity allows the study of a number of phenomena that cannot be adequately studied terrestrially, such as bubble dissolution by chemical fining agents in glass, bubble centering mechanisms in thin glass shells, bubble deformation and motion in a thermal gradient, ripening of precipitates or flocculates, nucleation and growth of immiscible phases, interaction of solidification fronts with bubbles or second-phase materials, or solidification of composites with large density differences, preparation of phase-separating glasses, and multiphase monotectic solidification.

Figure 15 illustrates the improved structure and homogeneous mixing in the space processing of metals and alloys, while figure 16 depicts the advantages of reduced gravity in the processing of organics and biological materials. Alloys are further discussed in the next section in connection with the NASA-Industry Guest Investigator program.

The separation of biological materials in space holds the promise of producing therapeutic quantities of pure pharmaceuticals not available on Earth. Biological purification processes can benefit from the absence of gravity because convection and sedimentation are essentially absent. Of particular interest are the continuous separation processes which can produce commercial quantities of important biological agents for medical applications and research.

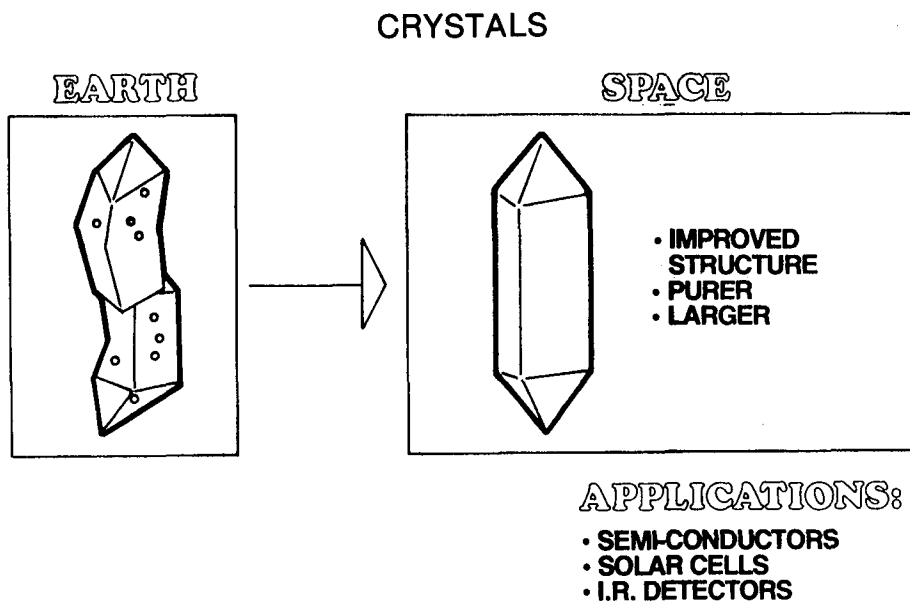


Figure 13

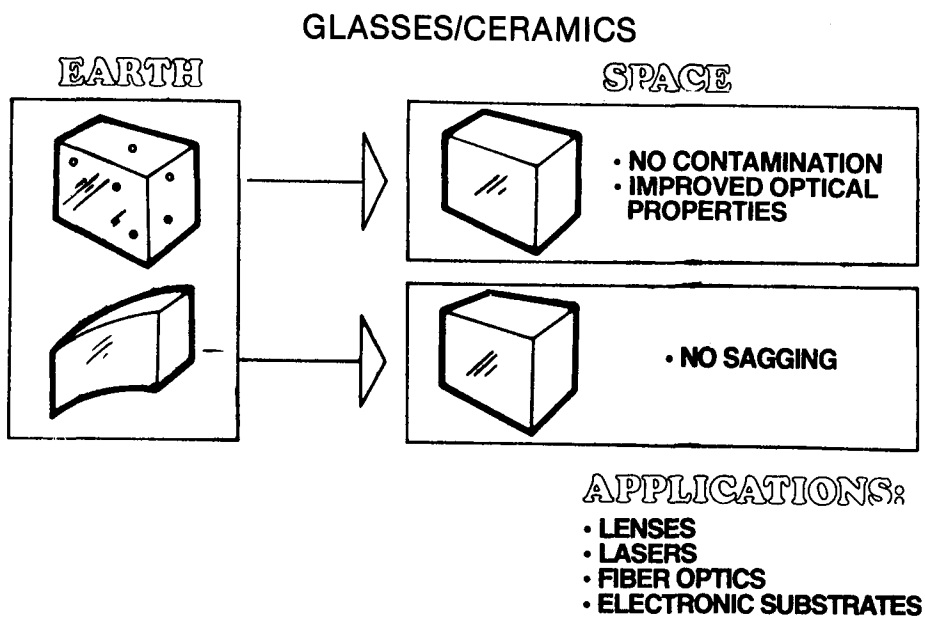


Figure 14

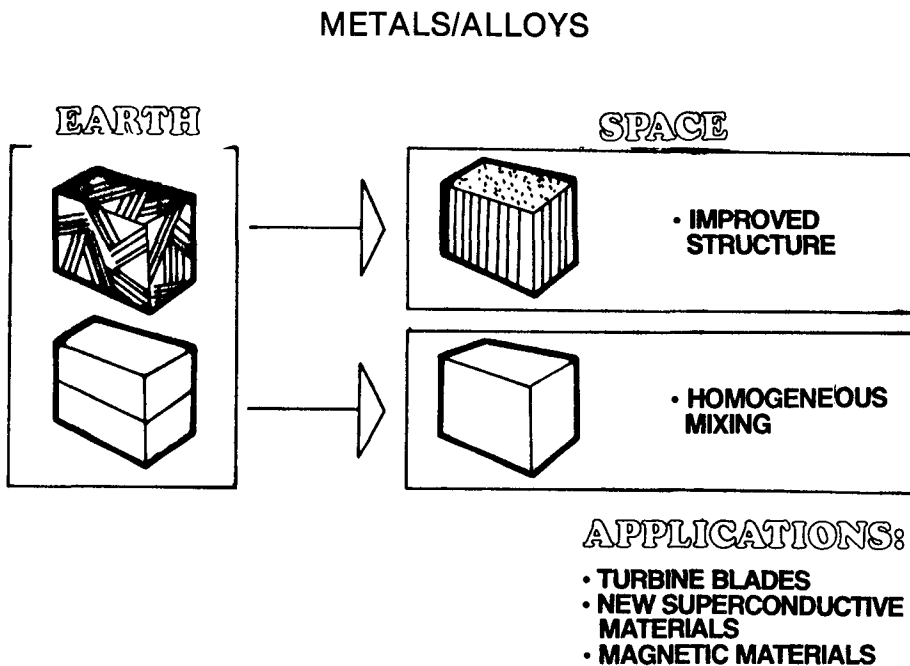


Figure 15

ORGANICS/BIOLOGICALS

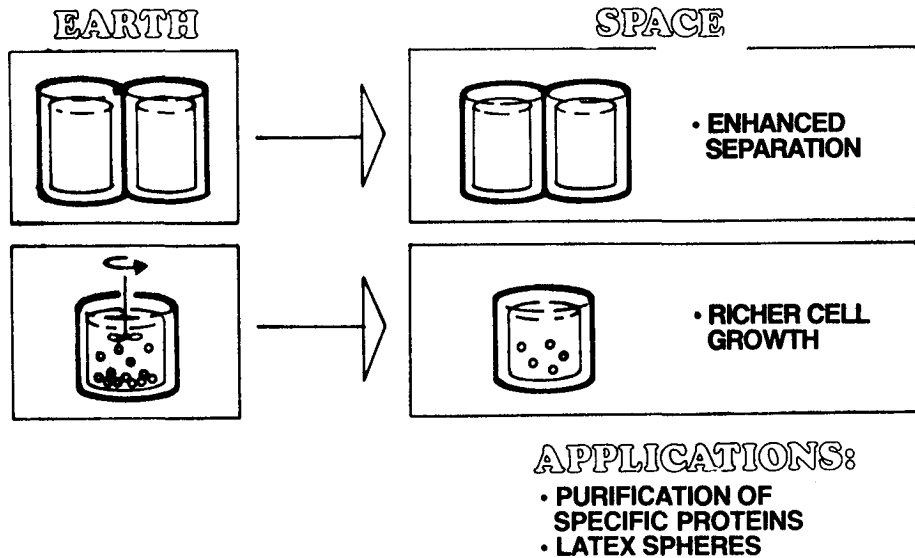


Figure 16

Isoelectric focusing is a type of electrophoresis where biological materials are separated by their differing mobility in an electric field. In isoelectric focusing the materials migrate in the electric field to a point in the nonuniform solution where they are electrically neutral. At this point they cease their migration and form a band. On Earth this band will broaden and overlap with bands of other materials, because of buoyancy and convection.

In continuous-flow isoelectric focusing there is a constant supply of a mixture of biological materials applied to a continuously flowing bed of electrolyte. The materials separate in the electrical field created by the electrodes at either end of the flow cell. They are carried from top to bottom in the cell by flowing electrolyte. At the bottom of the cell the electrolyte and separated biologicals exit the cell and are collected in various tubes. The now purified biologicals are collected in different tubes which, when filled, are stored for the return to Earth.

NASA'S Industrial Guest Investigator Program

NASA has a unique program underway to involve industrial scientists with NASA's appointed principal investigators. It is termed the "Industrial Guest Investigator" (IGI) program. Figure 17 summarizes the IGI program's characteristics.

NASA has recently approved IGI status for the TRW Equipment Group, Materials Technology Organization of Cleveland, Ohio. This is the first IGI proposal to be approved by NASA. Under this IGI agreement Mr. Jack Alexander, Dr. Tom Piwonka, and Mr. Mike Cybulsky of TRW Materials Technology (Mike Cybulsky is the actual TRW IGI) are working with Dr. Mary Helen Johnston of the NASA MSFC on space processing for solidification structures. Figure 18 provides a brief overview of TRW's IGI role.

Plan of Investigation

TRW Materials Technology has already embarked on the early stages of the first items singled out for investigation. The alloy that TRW and Dr. Johnston have selected is aluminum-4.5 percent

INDUSTRIAL GUEST INVESTIGATOR PROGRAM

WHAT IS AN INDUSTRIAL GUEST INVESTIGATOR?

- **INDUSTRIAL SCIENTIST**
- **NOMINATED BY INDUSTRIAL FIRM; MUTUALLY ACCEPTABLE BY NASA AND THE PRINCIPAL INVESTIGATOR (PI)**
- **ARRANGEMENTS WORKED ON A CASE-BY-CASE BASIS**

GUEST INVESTIGATOR INVOLVEMENTS

- **COORDINATES WITH A NASA PI**
- **SUGGESTS MATERIALS AND PROCESSES FOR INVESTIGATIONS**
- **CONDUCTS MPS GROUND-BASED RESEARCH**
- **INPUTS FUTURE NASA PLANNING**
- **ANALYZES FLIGHT DATA/SAMPLES**

**NO NASA FUNDING OF WORK DONE BY
GUEST INVESTIGATOR**

Figure 17

TRW'S INDUSTRIAL GUEST INVESTIGATOR (IGI) PROGRAM

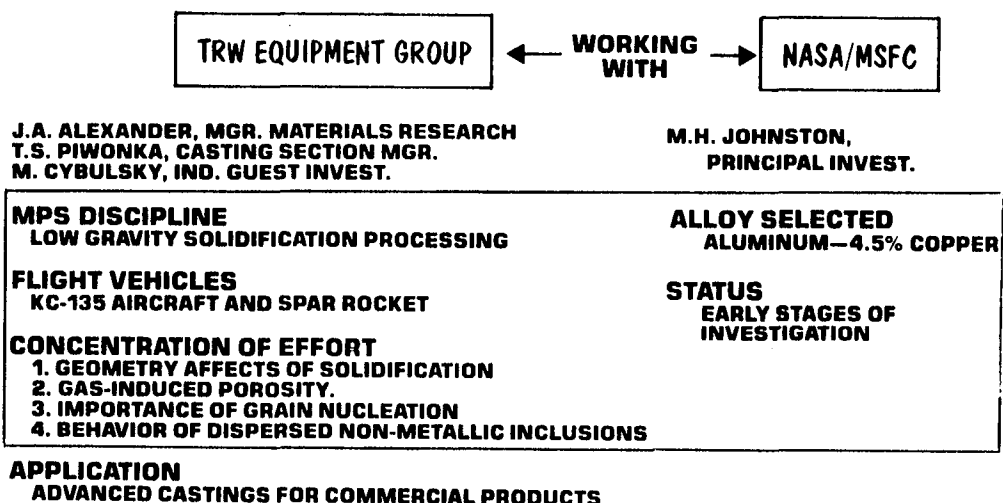


Figure 18

copper. This alloy has a melting point of 645° C, which is within the range of melting equipment on KC-135 airplane and SPAR rocket flights (figs. 19 and 20) and has been extensively studied in ground-based experiments. The copper within the alloy segregates during solidification in a straightforward manner which can be easily measured, and the molten alloy dissolves large quantities of hydrogen gas which is relatively insoluble in the solid. The alloy also has a long freezing range (100° C) which makes it particularly prone to the formation of shrinkage porosity, and it is known to respond to a number of nucleating agents which may be used to refine its grain size. It is therefore an

KC-135 CASTING FURNACE ASSEMBLY

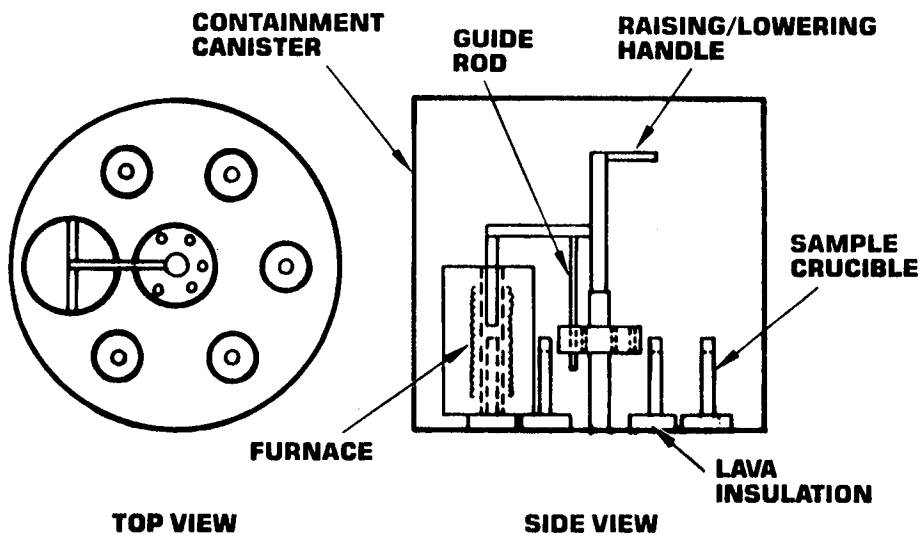


Figure 19

SPAR CANISTER ASSEMBLY SCHEMATIC

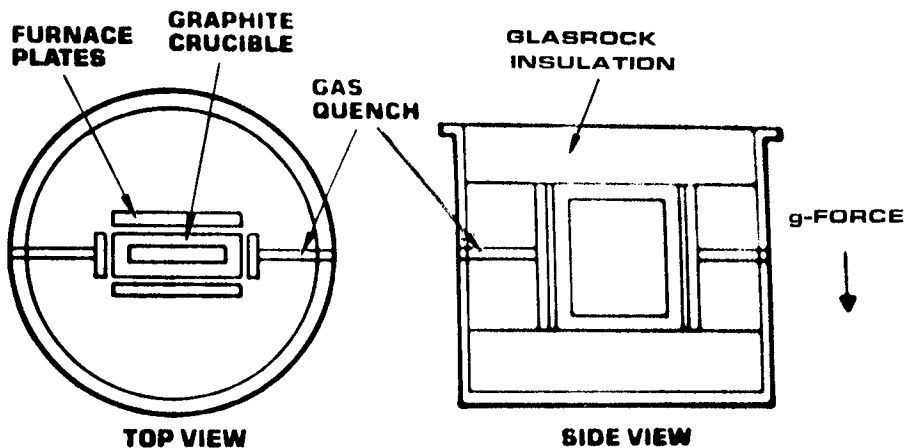


Figure 20

ideal alloy to use in these preliminary experiments. Figure 21 shows the Al-Cu phase diagram and porosity characteristics.

Studies of geometry affects of solidification are underway at present. KC-135 and SPAR flights will be flown in May to obtain baseline data on a straight-sided ingot. A very simple change, use of a tapered ingot instead of a straight-sided ingot, will be evaluated in a SPAR flight in July 1980. More complex section shapes will be introduced in subsequent SPAR flights, combining those experiments with investigations of porosity. These experiments are expected to define the extent to which knowledge of the effect of geometry on terrestrial solidification may be expected to transfer to space.

Gas-induced porosity will be evaluated in July KC-135 flights using Al-4.5%Cu ingot containing high and low levels of hydrogen. The purpose of these experiments is to establish the distribution of hydrogen bubbles as they are precipitated from the liquid-solid interface during solidification.

Shrinkage porosity will be studied by modifying ingot geometry from a straight-sided to a tapered configuration with one end smaller than the other. A second desirable geometry would be an X-shaped casting, because this shape concentrates heat at its center which then acts as a source of liquid to feed the arms of the casting.

Because of the importance of grain nucleation to the commercial foundry industry and the necessity of establishing the feasibility of simple grain refinement techniques for solidification processes, a series of experiments will be designed both to gain insight into current theories of grain nucleation and to act as a screening test for candidate nucleants. A baseline test, in which titanium inoculant is added to bulk sample of Al-4.5%Cu alloy, will be run as the first sample. All experiments will be run first on the ground, and then repeated in space.

The same technique can be used to study the behavior of nonmetallic inclusions during space solidification. A known quantity of oxides (for Al-4.5%Cu, Al_2O_3 would be used) will be distributed throughout an ingot and its locations recorded. After melting and solidification, both on the ground and in space, the ingots will be examined metallographically to determine what changes, if any, occur in its distribution. Specifically, what indication is there of agglomeration or inclusion movement as a result of gravity or the lack of it.

If it is found that nonmetallic particles remain suspended in their original positions in the ingot melted and solidified in space, then the possibility that space processing may be used to prepare

AL-4.5%Cu ALLOY SELECTED FOR IGI STUDIES

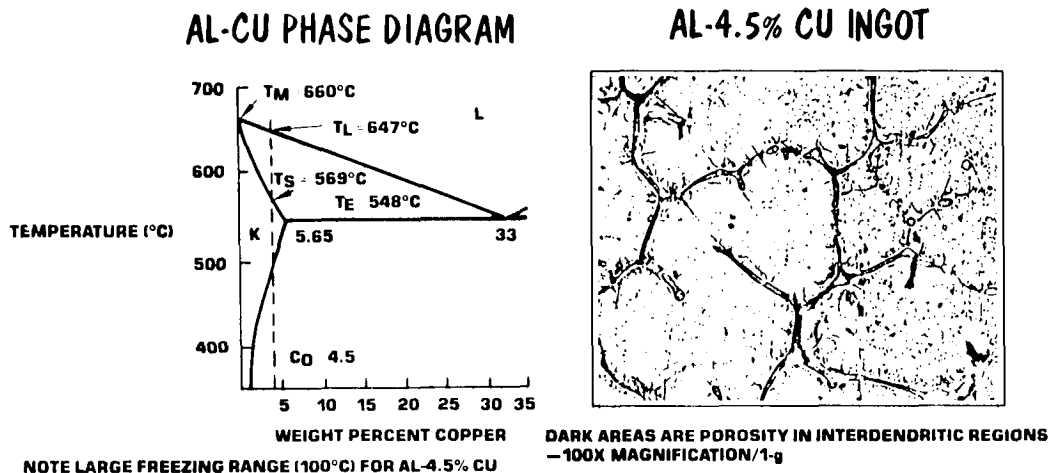


Figure 21

dispersion hardened solidification products (eutectics, single crystals, etc.) may be considered. This could be accomplished by building a directional solidification cell, preparing a powder compact containing the dispersion and the matrix material, placing the compact in the cell, and melting and directionally solidifying the compact. Feasibility of the concept can be demonstrated with Al-4.5%Cu alloy.

After feasibility has been demonstrated, a number of metallic systems will be designed and evaluated. Evaluation will consist of obtaining mechanical property data, corrosion property data, and other data of interest. All that remains then is to demonstrate that shaped castings can be made and an application for space processing is at hand.

Summary of the IGI Plan

TRW Materials Technology purposes to maintain its involvement with the NASA Space Processing program as guest investigators studying solidification processing. The thrust of our effort will be to study those phenomena which lead to the development of dispersion-hardened solidification structures, such as single crystals, for application in high corrosion, high temperature environments, such as fossile fuel energy generation systems. Specifically, the TRW IGI program with Dr. Johnston of MSFC involves planning to determine

- (1) The effect of geometry on space solidification patterns
- (2) The effect of very low gravity on void and pore formation
- (3) The effect of nonmetallic particles on nucleation of crystals during solidification in low gravity
- (4) The effect of low gravity on the distribution of nonmetallic particles during solidification
- (5) The feasibility of producing a dispersion-hardened solidification structure

Commercial Ventures

The ultimate goal of the Materials Processing in Space program is to develop commercial interests in using space to (1) perform research to improve industrial technology or to develop new products, (2) to prepare research quantities of material with which to compare current Earth-based technologies, (3) to manufacture limited quantities of a unique product to test market potential or to fulfill a limited but compelling need, and (4) to produce materials in space of sufficient quantity and value to stand on their own economically.

The four stages of implementation of the MPS program are shown in figure 22.

The nature of the fundamental research stage will require sustained flight opportunities by most investigations to satisfy their objectives. For this reason comprehensive government-sponsored investigatory studies rather than single-point or random opportunities are necessary.

A very active learning process will occur, particularly during the initial years (1983-86). Progress in space processing into products will be closely paced by the visibility the scientific and applications investigations afford to further exploitation and avenues of progress.

The process control demonstration stage (1985-88) will require a maturing of the Shuttle/Spacelab MPS payloads for use on longer missions—Shuttle sortie mode of MEC flights—as well as the development of new payload hardware. Before the program can expand, accurate control must occur over all the major processing events and sequences.

The progression into the product development stage (1988-90) must recognize that extension to space ventures will not grow from singular scientific curios. Thus, the thrust of this stage must be to conduct the extensive body of applications and preliminary product development work needed to translate information on novel materials and process inventions into the practical production processes and products. This stage, and the previous stage, should feature strong government and industry joint ventures.

Only the strongest candidates for reduction-to-practice efforts will survive. The present body of technical data is insufficient to rank the potential application areas which have been suggested to

MPS PROGRAM IMPLEMENTATION

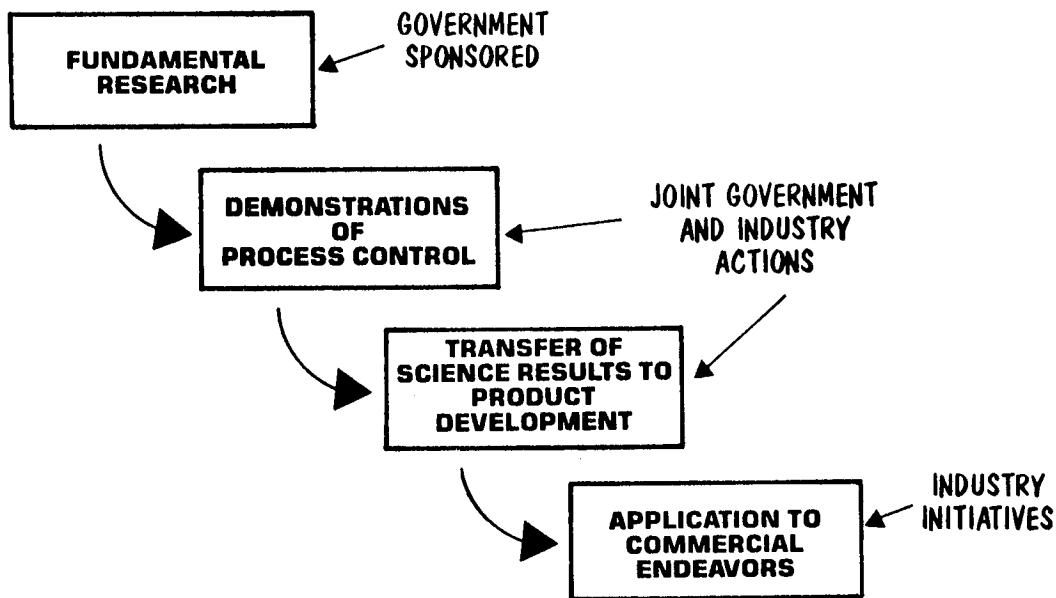


Figure 22

date. What is clear is the need to develop the proper activities during the early part of the product development stage in order to facilitate the selection of those areas in which to proceed. We can expect a follow-the-leader in related industries after the initial favorable result.

The application to commercial endeavors stage (1990–2000) will culminate in expression of commercial manufacturing. Industrialization, applied to space processing, refers to the production of either unique products—those which cannot be made on Earth—or of economic yields of a product which can be obtained in only limited quantities on Earth. Typically, such products would be of high value-added or would be an essential intermediate step in a manufacturing process.

Commercial industry will certainly wish to exploit the cheapest possible way to work in space. Highly specific facilities will be evolved and dedicated to individual product forms rather than general purpose capabilities which were appropriate to the previous stage. Use of the Shuttle for transport, national space facilities, or alternatives such as privately financed systems will undoubtedly be manifest. The evolution of space manufacturing complexes will be dictated by whether government financing or industrial risk capital dominates. Continued dominance of space access through governments will have to be replaced by alternatives in an expanded industrialization era.

The paragraphs above mentioned stages where the government or industry or both should sponsor the efforts. The prime distinction between government and industry can be summed as follows:

Government

- (1) Recognizes potential benefits and takes leadership
- (2) Sponsors high risk technology development
- (3) Focuses direction.

Aerospace industry

- (1) Knows and understands space
- (2) Develops, builds, and operates space systems.

Commercial industry

- (1) Knows the needs of the marketplace
- (2) Makes needs into products
- (3) Derives requirements for space vehicles and processing equipment.

Joint projects involving the government and industrial concerns will surely be the role sought by all parties.

Government Funding

NASA has sponsored space materials processing activities since the late 1960's. Figure 23 shows the fiscal year funding levels spent up to FY1980 and planned from FY1980 to FY1986. From 1968 to 1978 a total of about \$32 million was spent. The funding level has remained constant at about \$20 million a year for FY1979 to FY1982. Beyond FY1983, NASA plans to significantly increase the U.S. investment in MPS. The expenditures are planned to reach and stay at \$40 million a year in FY1984. This must occur. In fact, the \$40 million level is even considered marginal to foster commercial initiatives, to promote NASA/industry joint ventures, and to keep the U.S. technically competitive with international interests in space processing. Dynamic industrial countries are pursuing MPS, for example,

West Germany

- Has a comprehensive research program
- Purchased an entire Spacelab/Shuttle flight.

France

- Flew MPS experiments on Salyut 6
- Is planning an automated Spacelab.

Japan

- Is following the U.S. space program
- Is part of \$15 billion, 15-year space research allocation for MPS

USSR

- Obtained most MPS time through Salyut 6
- Has 350 materials scientists active in MPS

MATERIALS PROCESSING IN SPACE NASA FUNDING

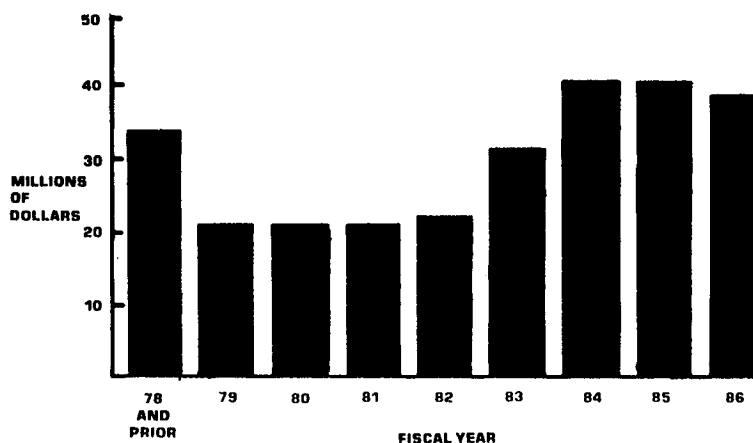


Figure 23

Summary

The space environment for materials processing should expand our perspectives of both the science and technology of materials. Enhancements in the control over the structure and properties of materials are the primary outputs expected from the processing investigations to be first performed in space on Shuttle/Spacelab 1983 missions. Results will undoubtedly benefit ground-based processes.

The unique capabilities of weightlessness are expected to be of benefit ultimately to a class of new, high value products. However, precursor products must first be made by the commercial sector to test the risks, including the investigation of competitive ground-based technologies, as well as the market demands for such materials. The tentative nature of cooperative opportunities to explore these possibilities is currently under consideration by a growing number of U.S. companies.

The availability of frequent and economical access to the space environment afforded by the Space Shuttle and vehicles to follow, like the Materials Experiment Carrier, will open new opportunities for materials research and new product lines for commercial interests.

A fundamental message is "As our business looks up, we must keep both feet on the ground." With the start of Shuttle/Spacelab MPS flights, there will be some exciting things to do. We will do some research; we will explore. But as the MPS investigations mature from materials development to materials applications, we must not forget that there are some very practical things that we are going to have to accomplish to make space productization a reality.

Planning for space commitments by individuals and organizations are required to implement and sustain such an endeavor. In the face of some skepticism and the always present competition for resources, a spirited endeavor is called for.

Most critical of all the issues is the involvement of industrial participants as soon as possible in the applications area. Their technical progress and business motivations will then lead to the resolution of the other factors.

The need to combine skills of the scientific/engineering community with those of management in government and industry is apparent. To bring focus, to achieve a critical mass of endeavor, and to incorporate industrial support is NASA's principal challenge. Industry must be enlisted to assist NASA in meeting this challenge.

Technology Transfer

Anthony J. Calio

*National Aeronautics and Space Administration
Washington, D. C.*

NASA's predecessor, the National Advisory Committee for Aeronautics (NACA), had a long history of cooperative ventures with the government and civil aeronautics organizations. When NACA became NASA in 1958 these cooperative efforts had to be greatly expanded to accommodate rapidly developing space technologies. In doing so, we found ourselves confronted by many complex questions which defied simple solutions. How could we determine what specific benefits would flow from space research? How could we best assure that those benefits would be used effectively? What would be the specific roles of government and industry? How would we address patent issues? Should the users pay additional costs for the benefits? These were only some of the questions we faced.

Two programs undertaken early in the space program, meteorology and communications, were drivers which quickly forced NASA into the technology transfer process. Following the successful demonstration of the Tiros weather satellites, operational responsibility was vested in the U.S. Weather Bureau. Similarly, once communications satellites had been proved through demonstrations, private industry became the developers and operators of these new space capabilities.

Lessons learned from these two programs and other experiences over the ensuing years served us well in developing a technology transfer philosophy that is solidly based and is organized to provide flexibility to adapt to changing situations.

During the 1960's, as our remote sensing technologies and ability to operate in space grew, it became evident that there was a tremendous potential to gain entirely new insights about our planet's resources. Exploring this potential with the Department of Agriculture, the Department of the Interior, and others, led to the development of an Earth resources satellite, Landsat 1, which was launched in 1972 and followed by two more Landsats.

Numerous tests and demonstrations over the past 8 years proved that an Earth resources satellite system could meet many needs. The U.S. Department of Agriculture is conducting a demonstration to determine the value of using remote sensing from Landsat to provide timely estimates of worldwide crop production. States and local governments are using the data to create inventories of land and water resources and to assess the effect of planned industrial development. Private firms are using the data in a variety of ways. The St. Regis Paper Company, for example, is now using satellite data in a digital information system to inventory their forest holdings and to monitor changes.

The results of NASA Landsat experiments and the long term potential that needs to be realized led to the President's decision last November to direct the creation of a fully operational land-oriented remote sensing system from space to be operated by the National Oceanic and Atmospheric Administration.

This brief overview of some of NASA's principal programs of the 1960's and 1970's is a clear indication of our intent to put new technologies into the hands of users.

So, what have we learned and where are we today? What we have learned is that if we can get the potential user on-board at the inception of a new technology program and keep him on-board as an active partner, the results will be readily realizable as profitable benefits, not only to the participants, but to the nation as well. In short, we need you—industry—to work with us to define those technological problems where our unique space expertise can be brought to bear, to work with us in seeking the solutions, and to stand ready to put the solutions to work.

This NASA/industry partnership is possible and is a necessary component in helping to maintain our national technological growth and strength. The best way to describe where we are today and how users are being involved is by illustration.

NASA's space communications program of the 1960's and early 1970's was phased down in 1973 with the expectation that funding of technological advances by the commercial communications industry would carry the national program in the future. However, the large number of dollars required to support this area of high-risk technology made it difficult for U.S. industry to maintain the technology lead it initially enjoyed.

Awareness of the changing U.S. position resulted in a recent national decision for NASA once more to sponsor the development of advanced satellite communications technologies. NASA is now proceeding with a revitalized research and development program in this highly critical area and in doing so has involved nearly every participant in satellite communications—government, industry, and university.

The knowledge and the guidance gained from these groups were combined with an intensive technical assessment of the current state-of-the-art and the potential for improvement in each major area of satellite communications. This activity, and a companion process used to identify "high leverage" research tasks, involving more than 100 organizations, led to a multiyear technology development plan. Further, to ensure that the plan is carried out as conceived, a committee of industry advisors has been formed. Five technologists and five service suppliers, meeting quarterly, review the objectives, technical approach, and results of the R&D program.

Thus, the NASA plan in satellite communications technology has undergone extensive scrutiny and received the endorsement of every major participant in the field. Further, the organization of the effort ensured rapid and effective technology transfer.

One of our most pressing national needs is to relieve the overcrowded frequencies where studies show that communications traffic demands will exceed the capacity of conventional satellites in the early 1990's. Under the agreed upon plan, NASA will fund research and development costs and design engineering, which is expected to take about 2 years. Upon completion, the need for flight tests of a complete or partial system to provide sufficient confidence for private industry to incorporate the technology into commercial operations will be evaluated. If we have been successful in our approach, there will be no need for a formal technology transfer process—industry will take it.

Our entry into remote sensing of the oceans presented us a mixed user group. In this case the users were other Government agencies, the scientific community, and commercial users, which we labeled the oceanographic community. While it was clear that the U.S. Navy would be an important beneficiary of an ocean satellite system, it was equally clear that important benefits would also flow to the commercial ocean industry as well as to climate researchers.

The first satellite dedicated to ocean remote sensing was Seasat, which was launched as a proof-of-concept mission. Although the mission ended prematurely, nearly 100 days of data were collected upon which to base an analysis of potential benefits. Participating in the analysis with the Government agencies were private industrial interests representing fisheries, deep ocean mining, offshore oil and gas operations, and marine shipping. Among these were Ocean Data System, Inc., Sun Shipbuilding and Dry Dock Co., North Pacific Fishing Vessel Owners Associations, Southwest Fisheries Laboratory, American Gas Association, Kennecott Exploration, Inc., Getty Oil Co., Esso Resources, Ltd.—over 30 organizations.

As a result of the Seasat analyses, we have embarked on a course to demonstrate a limited operational ocean satellite system. We have proposed to the Congress a national oceanic satellite system to be jointly funded by the Department of Defense, the National Oceanic and Atmospheric Administration, and NASA. NASA's role will be to direct the prototype development. If this operational demonstration is successful, the system will be directed by an operational agency to serve the user community.

As for materials processing in space, the steps we have taken in developing the program will provide us with new capabilities representing a fundamental increase in the limits of our perspectives on materials. We have a unique opportunity to build a laboratory which has characteristics no

installation on Earth could have: the zero-g environment. When you consider the effect of gravity on the processing of materials, it becomes clear there is a great deal that can be learned in the space environment where, for example, there is a means for separating gravity-driven from nongravity-driven flows and studying them separately. Many terrestrial processes can be improved or optimized by a better understanding of the science of materials processing. Past experiments led the way to new processes to prepare old materials with improved properties, such as occurred in unidirectional solidification of single-crystal turbine blades or continuous casting for steel ingots. We expect similar enhancements or totally new processes to result from our laboratory in space. Solidification processes, crystal growth, containerless processing, and chemical processes are but some of the materials experiments which may benefit from this unique laboratory.

The decision for NASA to make the up-front, high-risk investment in materials processing in space has been endorsed by the administration and by Congress as necessary to potential industrial growth in this field. In putting the program together, we sought and received the expertise from the materials science industry as partners, not only for their talent but because they will be the ultimate users.

My message to private industry is "Get involved." It is easier to do than you might imagine. We have policies and guidelines to stimulate and simplify your participation and we are encouraging commercially oriented investigations by means of NASA's space research programs.

Last summer, in statements entitled "NASA Guidelines Regarding Early Usage of Space for Industrial Purposes" and "Guidelines Regarding Joint Endeavors with U.S. Domestic Concerns in Materials Processing in Space," we proposed three avenues for industry's entry into space-related research programs. The first of these is the technical exchange, a minimal cost way for interested companies to become more familiar with and use specific NASA research capabilities as they may relate to their own specific needs. It is essentially a low-key approach for a firm and NASA to exchange technical information and cooperate in data analysis from on-going ground based research.

The next level of participation is the Industrial Guest Investigator Program designed to gain early commercial involvement in a specific NASA research program and expedite the technology transfer into commercial applications. In this program the guest investigator, an industrial scientist, collaborates with a NASA principal investigator in suggesting processes for investigation, in conducting ground based research, in performing postflight analyses of data, samples, or processes, and in making inputs on future planning.

The third avenue open to industry is the joint endeavor. It is an agreement, rather than a procurement contract which, among other things, does not require that NASA take patent and data rights. A wide range of factors affecting the endeavor and its outcome are subject to negotiations on a case-by-case basis, with each joint endeavor specifically tailored to meet NASA's and the partner's needs. Under a joint endeavor the private firm's portion of the agreement may include ground based research, experiment payload development, data analysis, market studies, and all commercial phases costs. NASA's portion may include ground based research, Shuttle transportation services, payload integration, and technical assistance with NASA procedures.

What we have been discussing so far are the direct transfers of technology from NASA primary programs undertaken with much industry participation. Not to be overlooked are the secondary transfers of technology: applications of aerospace related new technology to uses different, sometimes remote, from the original application. These applications, called spinoffs, have yielded widespread and significant benefits to many segments of our population with economic values often running into millions of dollars.

The NASA technology utilization program, an organized technology transfer effort, exists specifically for businesses like yours. An aggressive new technology reporting and publication effort is the first part of industrial transfer.

NASA R&D contractors and NASA employees are required to report all new innovations and inventions resulting from aerospace R&D. These innovations and inventions are reviewed for originality and potential utility in nonaerospace applications. After screening, all relevant innovations are published in abstracted form as one- or two-page briefs in NASA's quarterly Tech Brief Journal. The Tech Brief Journal is distributed at no cost to a subscriber list, currently about

66 000 strong. Primarily for industrial and technical recipients, Tech Briefs are also distributed to public libraries and to state and local engineers on request. A subscriber, using a reader service card, can request a substantially more detailed back-up report, called a technical support package, for any Tech Brief.

A second part of our effort is to promote technology transfer through a nationwide data bank service. NASA operates a network of Industrial Applications Centers (IACS) whose job it is to provide automated information retrieval services and technical assistance to industrial clients. The network's principal resource is a vast storehouse of accumulated technical knowledge, computerized for ready retrieval.

Through the IACS, industry has access to some 10 million documents, the world's largest repository of technical data. About 1.5 million of these documents are NASA reports covering every field of aerospace activity. In addition, the data bank includes the continually updated contents of 15 000 scientific and technical journals, plus thousands of published and unpublished reports compiled by industrial researchers and by government agencies other than NASA. Each month another 50 000 documents are added to this wealth of technical information.

The IACS seek to broaden and expedite technology transfer by helping industry to find and apply information pertinent to a company's projects or problems. The philosophy behind the IACS is that it is wasteful to reinvent the wheel, that there is no need to duplicate research already thoroughly documented in the data bank. By taking advantage of IAC services, individual businesses can save time and money, and the nation benefits as well.

The IACS are located at university campuses across the country, each serving a geographical concentration of industry; they also have off-site representatives serving industrial clients in many major cities and their surrounding areas. Additionally, there are IAC technology coordinators at six NASA field centers who perform the important function of matching on-going NASA research and engineering with client interests.

Staffed by scientists, engineers, and computer retrieval specialists experienced in working with companies, the centers provide various services. To an industrial firm contemplating a new research and development program or seeking to solve a problem, they offer retrospective searches; they probe the data bank for relevant literature and provide abstracts or full-text reports on subjects applicable to the company's needs. IACS also provide current awareness services, tailored periodic reports designed to keep a company's executives or engineers abreast of the latest developments in their fields with a minimal investment of time.

A related service to industry is provided by NASA's computer software management and information center (COSMIC) at the University of Georgia. COSMIC collects, screens, and stores computer programs developed by NASA and other government agencies. Adaptable to secondary use by industry, government, or other organizations, these programs perform such tasks as structural analysis, electronic circuit design, chemical analysis, design of fluid systems, determination of building energy requirements, and a variety of other functions. COSMIC maintains a library of some 1600 computer programs, which are available to users at a fraction of their original cost. This facet of NASA's industrial service effort represents a large and successful area of technology transfer.

More detailed descriptions of these and other technology transfer mechanisms are included in the NASA Technology Utilization Program report, "Spinoff." The names and locations of these Centers are also included.

In efforts to improve our ability to transfer technology directly to U.S. industry, conferences like this one play an important role, as do our involvement and cooperation with industry associations and professional societies.

Perhaps the best indication of the philosophy of the agency and of the effort to promote use of NASA technology to benefit the economy is the effort put forth by the Lewis Research Center personnel in promoting and managing conferences such as this. The Technology Utilization (TU) Office here at Lewis has done an outstanding job, and the individual scientists and engineers giving talks and demonstrations are enthusiastically sharing their laboratory results with you in the best spirit of technology transfer. As a matter of fact, one of the best and easiest ways to start making use

of the NASA TU Program is to write or call the TU Officer at a NASA field center. There is a list in "Spinoff." (At Lewis, call (216) 433-4000, Ext. 422.)

To repeat, we have had to resolve many complex issues over the past 20 years concerning technology transfer. But we are resolving them. We are learning from them. In the process, NASA and industry space research programs have made many substantial contributions to our society, such as new technologies in integrated circuitry, in gas turbines for electric power generation, in biomedical devices like the rechargeable pacemaker—the list goes on.

NASA recognizes industry's vital role as a partner in developing and putting new technologies to use. We know industry often has reservations and questions about doing business with The Government. We believe NASA has faced and overcome many of these. For those remaining, let's talk! There is great national and individual gain to be made by the productive partnership of industry and NASA in technology transfer.

Technology—Key to the Future*

E. Mandell deWindt†

*Eaton Corporation
Cleveland, Ohio*

At 9:32 a.m., precisely on schedule, on July 16, 1969, three American travelers departed on a long journey. The fare for the trio was estimated at \$25 billion dollars. It was a bargain.

That "giant leap for mankind" to the surface of the moon, brought with it a veritable cascade of technological advances that have benefited people everywhere ever since. From significant breakthroughs in medicine to new materials and processes in manufacturing to sophisticated progress in computers and communications, the technology of space has come down to Earth with a solid impact.

One of the favorite stories of almost every business speaker in recent years is the old chestnut that begins with, "What are the three least reassuring statements of all time? The first is always, "Your check is in the mail," and the punch line that helps win the audience's applause and sympathy is, "Hi, I'm here from the government, I'm here to help you."

Here today, fortunately, that quip—to use a once-popular governmental cliché—is inoperative. NASA and, especially, the Lewis Research Center is here to help, and this conference on Technology Utilization is specific and concrete evidence that the help it offers is real and wanted.

The subjects being discussed and demonstrated in these two days are more than examples of advanced technology; they strike at the very heart of our current problems and literally hold the key to much of our nation's future.

The challenge of the 80's for American industry is fraught with both danger and opportunity. The danger lies in slowing productivity and eroding technological leadership. The opportunity to vault these problems and lead the way into a productive and prosperous 21st century is also at hand. It is going to take some doing, however, and the rapid dissemination and utilization of technology available from NASA Lewis Research Center can play a major role.

Lewis is a unique and exciting operation. For 38 years it has pioneered in the technology of engine propulsion for aircraft and space vehicles. Over the years, its mission, facilities, and staff have expanded considerably and today, in addition to being the aerospace propulsion capital of the world, it encompasses a broad spectrum of technology that includes renewable and storable energy, satellite communications systems, and a wealth of information on materials and processes for industry.

Getting "down to Earth" with space technology is the goal of this conference and all of us would be well advised to take full advantage of it: First of all, because we have invested in it and, second, because it offers the opportunity for some of the technological leaps that must be taken if the United States is to regain the aggressiveness and innovation to maintain and strengthen the technological superiority that has been the hallmark of our progress.

While technology is the subject at hand, it is also well to remember that the Lewis Research Center is a valuable community resource. The 3000 employees of Lewis, nearly half of whom are professional engineers and scientists, participate in community life and bring their special talents to bear on community problems. The educational aspects of Lewis and the Center's efforts in working

* After dinner address.

† Chairman of the board, the Eaton Corporation.

with educators and students have given our area an unequaled educational resource. In its Director, John F. McCarthy, Jr., Lewis has at the helm a man whose success in industry and education as well as government service brings a rare balance and understanding on how to be a part of the community as well as a vital link in NASA. I have to admit some personal bias toward Lewis and its people—both from the community and industrial point of view. Ten years ago, when Cleveland got together to face a growing problem in community concern and build the finest United Way Program in the Nation, Dr. Ted Olson was one of the prime movers and NASA Lewis was one of the most cooperative organizations. I might add that Ted Olson has been a mover on the community scene in many causes.

At a time when the image and morale of the Cleveland Area had hit new lows, the work advanced by Lewis Research Center brought encouraging reassurance that Cleveland is still a leader in engineering and science. Cleveland is an engineer oriented community and the successful programs at Lewis give encouragement and challenge to the entire professional fraternity. From the Lewis cyclotron treating patients at the famous Cleveland Clinic to Lewis educational programs that excite students throughout the Cleveland area, the research center plays a vital role in Cleveland's everyday life, as well as being an outstanding national asset.

On the business side of the ledger, Eaton and Lewis have had a number of relationships. A most recent example has some interesting ramifications.

Not too long ago, Eaton submitted to Lewis Research Center our proposal for an improved electric propulsion system for the Department of Energy's electric vehicle development program. We were confident that we had the background and the dedication to be a significant contributor to this emerging technology. And we liked the philosophy and practice of the Lewis people who are striving to bring electric vehicle propulsion to commercial as well as technological success. Our proposal received an enthusiastic go-ahead.

So, later this summer Eaton will be delivering for Lewis lab evaluation an experimental prototype of its lightweight ac electric propulsion system. Its ac drivemotor and transaxle are integrally packaged and its dc-to-ac power converter and controller, of innovative design, were built on a shared-cost basis. We are proud to be partners with NASA in this project, and we appreciate the confidence and cooperation of the Lewis Research Center.

Perhaps you wonder why Eaton had to get in on the electric highway vehicle act? Well, we felt that there was more to a practical mass-produceable car than finding a super-long-life battery. Of course, we do not make batteries, and we do not make cars. We do, however, make automobile and truck components. Also, we have for years been building production electric vehicles in the form of industrial lift trucks, and we have been a major supplier of adjustable speed electric drives for industry. Eaton pioneered the two-speed truck axle, and our research on automotive engines and drive-train components is extensive. It is very unlikely that we will get into the business of producing electric cars, but, as with almost every car built, Eaton will be a supplier of vital components.

Other projects we are currently involved in with Lewis and with the DOE include regenerative braking for vehicles, engine-valve technology, and computer modeling of the overall electric vehicle drive system.

Eaton has also gained from the NASA-developed technology of the kind you are seeing today. We use NASTRAN, the finite-element computer program developed here, to optimize the structural design of truck axles. Lewis-developed technology in composite materials and engine test and analysis is also helping to provide better Eaton products.

I mention our relationships with Lewis only to present first-hand, tangible evidence that the utilization of technology offered by NASA is valuable. There are boundless opportunities for all of us in industry to be saved from "reinventing the wheel" by applying the technologies and analytical programs that Lewis already has available.

Eaton and Lewis do have a common thread in the way we do things. Lewis does not do manned space missions, but not one of those fiery monsters would get off the pad without Lewis know-how. Eaton does not build cars or trucks, but most of them would still be in their garages without Eaton's

contributions. Neither of us is the glamour boy of our particular industry but we have an exciting and rewarding role to play.

The utilization of technology is more than just exciting; it is an utmost necessity in meeting the problems of today and the promises of the future. There is growing evidence that our nation is slowly but steadily slipping into what I term technological complacency. We are certainly the world's leaders in technology, but the others are catching up...FAST. I suppose that we could shrug our shoulders and point to American achievements in aerospace, data and word processing, advanced electronics, and other fields and scoff at any suggestion that we are losing ground.

But the facts tell another story.

In commercial aviation, an American exclusive since the beginning, the European consortium building the "Airbus" has come from nowhere to become the world's second largest airframe producer. In military aircraft there are gnawing and painful questions being raised about the reliability and operational capabilities of our most advanced fighters and helicopters.

Satellite communications systems, born and raised in the United States, have been improved upon by other nations.

In Montefiore, Italy, a Fiat automobile production plant has completely robotized and computerized welding and assembly lines with equipment that cannot be matched by any U.S. automaker.

In the midfifties the National Science Board reported that 75 to 80 percent of major technological innovations originated in the United States. By the seventies, that proportion had dropped to just over half.

When we consider spending our basic research, there are some startling facts. France, Japan, and West Germany are spending more money on the advancement of knowledge. I do not mean a greater percentage of GNP, but more actual dollars. The return on investment is slow, and the risk is high in basic research; but it has traditionally been the most profitable, spawning entire new industries.

For total research and development, U.S. spending as a percentage of GNP continued to drop from 3 percent in the midsixties to 2.2 percent today. The drop is even more damaging when we realize that one-half of the \$52 billion spent on R&D in the U.S. in 1979 went to complying with government regulations and a good share of the research is aimed at those same regulations, rather than being allocated to new products and processes.

The most disconcerting factor of all concerning America's technological strength is our snail-paced rate of productivity gain.

I am convinced that a sharp rise in productivity is the fastest and most effective answer to recession and inflation. I am equally convinced that technology holds the key to that needed productivity gain.

The fact is, however, that the annual 3 percent productivity gain that used to happen without seeming to try, now looks like an impossible dream.

The various items I have mentioned are not intended to be a documentation of technological slowdown. They are warning signals. The danger signs of technological complacency.

The reasons are varied. It is easy enough to point to government regulations and cry "foul" but the government has nothing to do with a company's decision to sacrifice long-term research in favor of short-term marketing goals. We cannot blame the government for the smaller number of engineers and scientists engaged in private industry. I will admit to being a vocal opponent of excessive government regulation, but I am equally concerned that business itself has lost some of its zest for adventure in research; some of its aggressiveness in finding new worlds to conquer; some of the innovative spirit. In short, we just may be suffering from technological complacency. One of the surest ways to stick a pin into our collective imaginations, is to take advantage of federally funded research. One observer noted that there are more than 800 federally funded research centers in the U.S., a virtually untapped reservoir of ideas, hardware, publications, programs, and projects that could lead to profitable commercial ventures. The most consistent and most successful U.S. leadership in technology has been in argiculture. No other nation can begin to match U.S. productivity and technological progress in argiculture.

It is more than a coincidence that American agriculture is the largest user of federally funded research.

Whether we call it technology transfer, utilization, or commercialization, getting back our own investments in government research, not only makes sense, it can help restore our technological aggressiveness. NASA estimates, for instance, that technology utilization by the private sector results in a 7-to-1 return on investment.

Professor Samuel Doctor, of the University of Pittsburgh, recently commented in hearings on technology transfer that, "Technology transfer is not document dissemination. It is, among other things, risk-taking, entrepreneurship, venturing, creative adaptation."

Your participation in this meeting is evidence that you want to be among the adventurers, the darers, and the doers. I am convinced that you have come to the right place. NASA's aggressive program of technology utilization has taken many forms but none is more effective than the face-to-face and person-to-person relationships that can be formed in these two days.

As I looked over the program for this conference and saw the wide range of possibilities for technological utilization, I was somewhat awed by the scope of activities being pursued here at Lewis: everything from lubrication and bearings to aircraft propulsion.

It is obvious that innovation and imagination are alive and well here. It is encouraging to note that all of this and much more came from America's dramatic decision to explore space. The spinoffs and rub-offs of that program, are not merely coincidental elements of the program. They are providing us with real and lasting benefits.

I am sure that Thomas Edison would enjoy being here today. Lewis has a lot of the spirit and technological drive that marked Edison's famous Menlo Park Laboratory. He called Menlo Park "an invention factory" and considered himself, not a scientist, but a "commercial inventor." He would find this conference on putting advanced technology into industrial practice right down his alley.

On the other hand, Edison would have found today's technological climate a little hard to take.

Let us take a fanciful journey back to the invention of the electric light at Menlo Park in 1879 and superimpose some of today's actions.

After successfully demonstrating the carbon-filament lamp that would soon transform night into day for millions of people everywhere, Edison would have to contend with the following:

The SEC would begin a probe of Edison's ties to the Morgans and Vanderbilts, who had put up \$50 000 to back the development of the incandescent lamp—a feat that had eluded inventors for half a century.

Next, the FTC would get into the act, charging that Edison's effort was unfair competition for gas lights.

The Consumer Product Safety Commission would determine that light bulbs were unsafe for children and production would have to stop until shock-proof electricity was discovered.

The FDA would announce that experiments with laboratory mice showed constant exposure to electric light caused glaucoma in 2 percent of the animals tested and thus, should be banned.

OSHA, in the meantime, would close the Menlo Park facility because of obvious safety hazards involving electricity.

A man from the OEO would deliver a citation noting that the Edison Electric Company was doing a very poor job of affirmative action. And, oh yes, there would be a letter in the mail from the IRS.

To top off his day, Edison would find a memo from his Board of Directors that would note that as of this day, his ROI, ROCE, and pre-tax earnings were far below their expectations.

All of us here need to encourage the innovators and work to make the regulatory bureaucrats part of a responsible and responsive government. We need to recapture the sense of adventure that took us into space.

We need men and women eager to pursue impossible dreams without the unrealistic shackles of over-regulation. The Thomas Edisons and Robert Goddards of this world are far too few and too precious to squander in filling out unnecessary forms.

All of us here need to encourage innovation. We have got to get involved personally in shaping public policy and, at the same time, make sure that our own organizations are not infected with burdensome bureaucracy.

We need to recapture the spirit of adventure that took us so successfully into space. We need to encourage the talented men and women who are eager to chase impossible dreams.

This trip to Lewis Research Center helps all of us restore our confidence in America's technological capability.

I hope that it also encourages us to get involved personally in restoring aggressiveness and innovation in our own research efforts so that we can regain unchallenged superiority in technology.

As I drove into the Lewis Research Center today, a sign along the road caught my eye and fired my imagination. It is a very simple sign containing the NASA logo and beneath it the words "For all mankind."

It is a noble and meaningful phrase and I could not help thinking that it should and could apply to what America and Americans are all about. I am convinced that the people of NASA and Lewis Research Center are motivated and guided by that motto. They certainly can be proud of their common efforts in working "for all mankind."

Lewis Research Center

Tour Stops

Ion Beam Applications

Bruce A. Banks

To utilize fully the technology resulting from the Lewis development of ion thrusters, a concerted effort has been made to identify, evaluate, and develop nonpropulsive applications of this technology. In one application, sputter etching, the electron bombardment ion source and vacuum facility used are low-cost adaptations of similar devices developed for propulsion in space.

Surface treatment by ion beam sputtering is carried out in a vacuum tank. For the ion beam source, argon, an inert gas that is easily ionized, is introduced into the cylindrical main discharge chamber (fig. 1). In this chamber electrons are emitted from a cathode under the influence of a magnetic field and then spiral with low energy toward a positive anode. At the operating pressure in the chamber the emitted electrons encounter ionizing collisions with argon atoms. A magnetic field is applied in order to increase the electron mean path and thus enhance the ionization process within the limited dimension of the discharge chamber. High electric fields between the acceleration grids at one end of the discharge chamber accelerate the argon ions discharging from the grids to high velocity. These ions are directed onto the surface of the material either to sputter clean or etch it (figs. 2 and 3). Research with this technique has resulted in the development of surface textures that improve the usefulness of various materials for many aerospace, industrial, biomedical, and energy applications.

Fluoropolymers such as Teflon can now be sputter textured and adhesively bonded, with substantial improvements in bond strength over state-of-the-art bonding techniques (fig. 4). In addition to adhesive bonding applications, the textured fluoropolymer surfaces are ideal surfaces for improved adherence of electroplated copper coatings. Textured fluoropolymer surfaces also allow textures to be produced on a wide variety of biopolymers by means of transfer casting techniques.

BASIC SCHEMATIC FOR ELECTRON BOMBARDMENT ION SOURCE

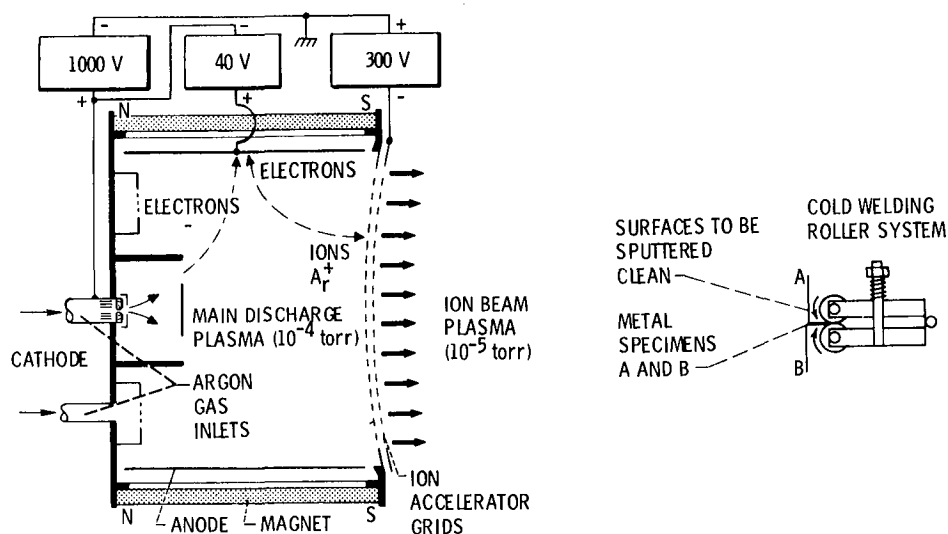


Figure 1

ION-BEAM-TEXTURED PTFE FLUOROPOLYMER

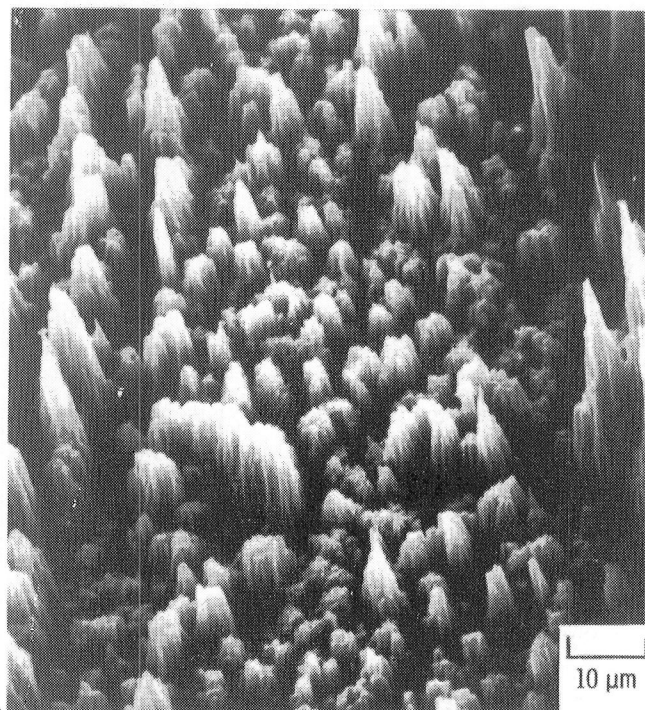


Figure 2

ION-BEAM-TEXTURED SURGICAL STAINLESS STEEL

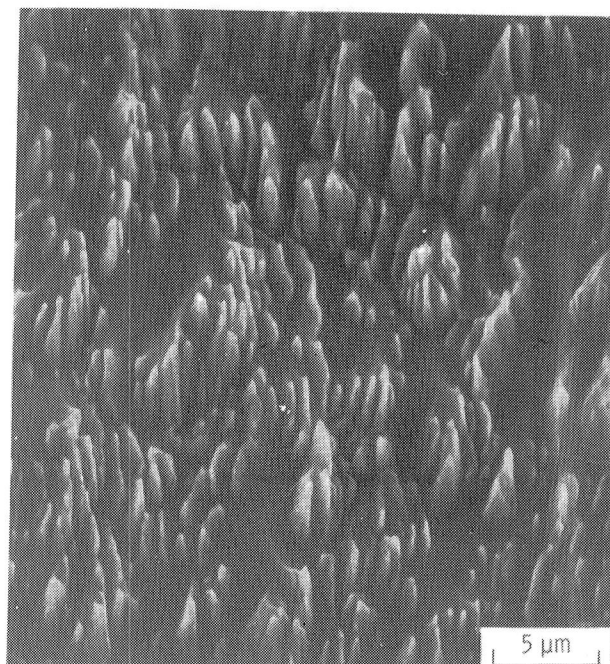


Figure 3

TENSILE AND SHEAR STRENGTH

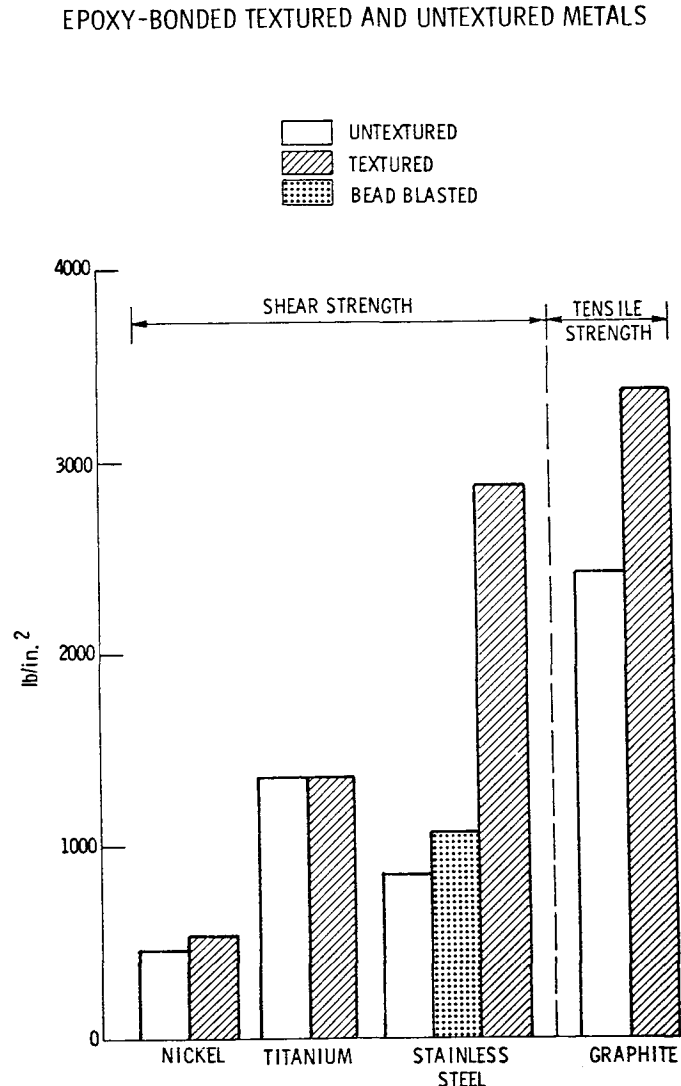
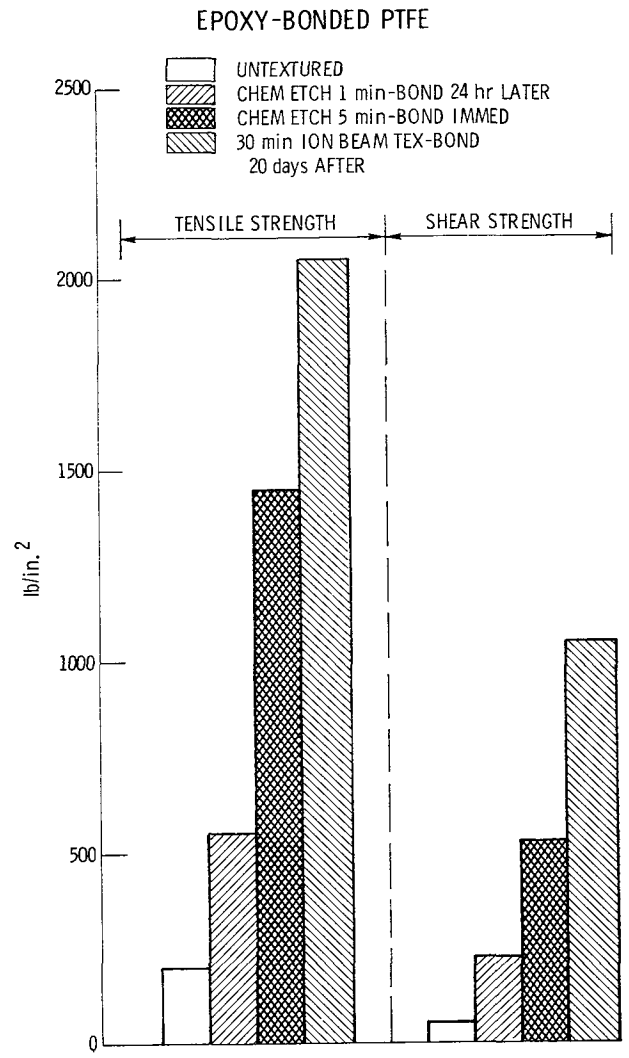


Figure 4

Thus biopolymers such as silicone rubber and segmented polyurethanes can be produced in the form of a surgical implant with surface textures suitable for tissue or cellular attachment (e.g., for plastic surgery or for cardiovascular prostheses). Ion beam sputtering of various polymers and metals used as biological implant materials can produce a controlled microscopic roughening of the surface of these materials. This controlled roughening has the potential to improve the performance of prosthetic materials (synthetic materials used to replace natural tissue or organs).

Ion beam sputter cleaning has been demonstrated as an effective technique for surface cleaning prior to cold welding of materials. Used before ion beam sputter deposition, it has resulted in significantly stronger bonds than are possible by conventional vacuum sputtering processes. These adherent coatings are now being evaluated for their effectiveness in increasing the lifetime of aluminum casting dies.

Ion beam surface treatment has shown a potential for numerous applications such as

1. The deposition of
 - a. Fluoropolymer films for the manufacturing of electronic components
 - b. Teflon, molybdenum disulfide, and carbon (or graphite) as lubricants
 - c. Adherent coatings of insulating materials such as silicon dioxide and aluminum oxide
2. The texturing of material surfaces
 - a. To modify reflectance and emissivity in order to expand the surface area and thus increase adsorption characteristics
 - b. To promote adhesion by microscopic roughening of a surface
 - c. To reduce secondary electron emission and reflected primary electrons in traveling-wave-tube depressed collectors
 - d. To produce a uniform parallel surface alinement on liquid crystal display substrates to improve display contrast
3. Ion beam drilling, sawing, and polishing of materials
4. The creation of composite materials by simultaneously sputtering targets that are composed of more than one material.

Magnetic Heat Pump

Gerald V. Brown

Magnetic materials can absorb and discharge substantial quantities of heat near their Curie temperatures when they are subjected to a cyclically applied magnetic field. This physical principle can be applied to pump heat across a temperature span that is large enough for useful heating and cooling applications.

The principle was demonstrated at this conference with a laboratory model operating as a magnetic heat engine (fig. 1). Cold and hot water alternately flow through a series of gadolinium plates, rendering the gadolinium first magnetic and then nonmagnetic. A permanent magnet on a rocker arm and a crank is alternately pulled toward the gadolinium by the magnetic field and pulled away from it by the momentum of a flywheel to which the rocker arm is linked. Solenoid valves controlling the cold and hot water streams are positioned by signal from an optical sensor that detects the flywheel position. Speeds to 350 rpm were demonstrated.

Magnetic heat pumping can be demonstrated by oscillating a grid of magnetic material, for example, gadolinium, through a vertical column of liquid (a regenerator) (fig. 2). A magnetic field is applied to magnetize and heat the gadolinium when it is at the top of the regenerator; the field is then cancelled and the gadolinium cools at the bottom of the regenerator tube. Additional cycles build a temperature gradient in the fluid. Ideally, the processes in the cycle are (1) isothermal magnetization, (2) cooling of the gadolinium in the regenerator (field on), (3) isothermal demagnetization, and (4) heating of the gadolinium in the regenerator (field off). Temperatures of -20°F at the bottom and 120°F at the top of a water-alcohol column have been achieved in the laboratory.

As one approach to a practical refrigeration device, cold and hot fluids would circulate externally from ports at each end of a liquid column containing the magnetic material, for example, gadolinium (fig. 3). A superconducting electromagnet operating continuously would provide a high field strength from low electric power. The magnetic material would be moved in and out of the field by an actuator, and the necessary heat transfer in the cycle would be achieved by a second actuator moving the liquid column relative to the magnetic material. The motions are analogous to those of a Stirling cycle engine.

Although the principle has been demonstrated in the laboratory, a number of questions pertinent to development remain: for example, materials properties; relations among magnetic field strength, heat transfer in the regenerator, and efficiency; and types of magnets. The advantages of the systems envisioned may accrue from the inherently high efficiency and from such simplifications as the absence of compressors, Freons, and high-pressure seals. Obvious potential applications include air conditioning, space heating, industrial refrigeration, or gas liquefaction. Some calculations indicate that capital and operating costs of a magnetic refrigerator with a helium-cooled superconducting magnet would not be prohibitive for a design size of at least 50 to 100 kilowatts of cooling or heating. Smaller machines with superconducting magnets probably would not be economical, and the utility of permanent magnets has not been explored.

LABORATORY MODEL OPERATING AS MAGNETIC HEAT ENGINE

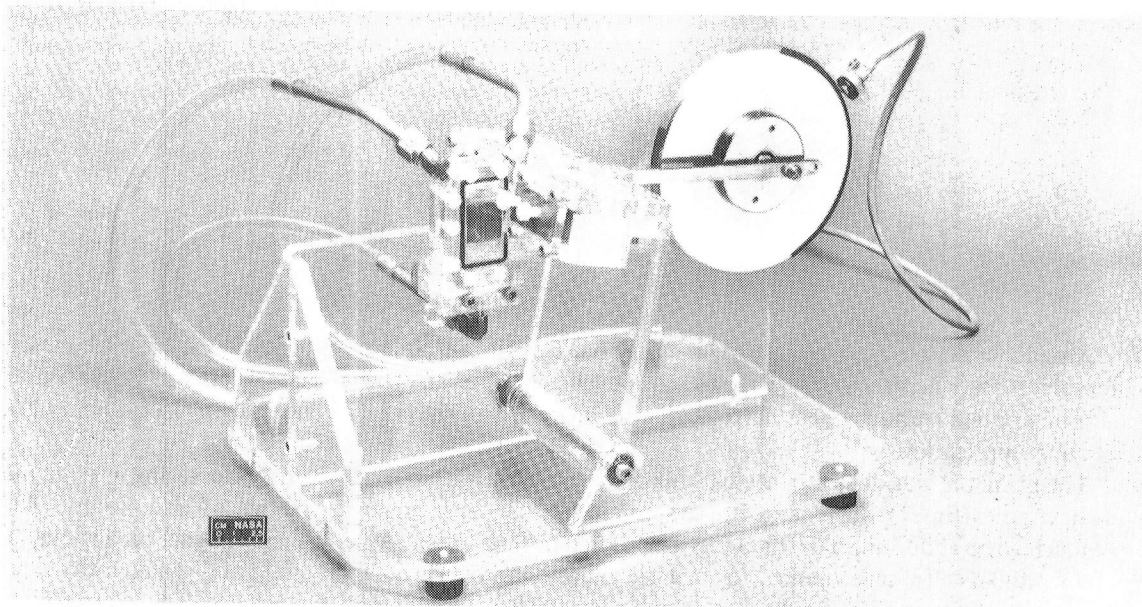


Figure 1

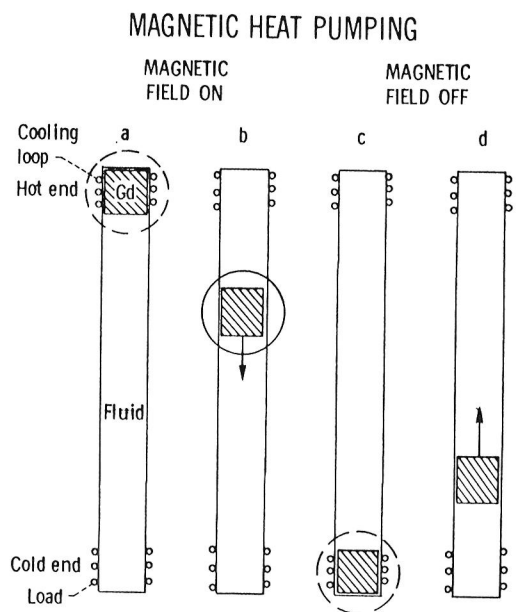


Figure 2

MAGNETIC HEAT PUMP

(ONE POSSIBLE CONFIGURATION)

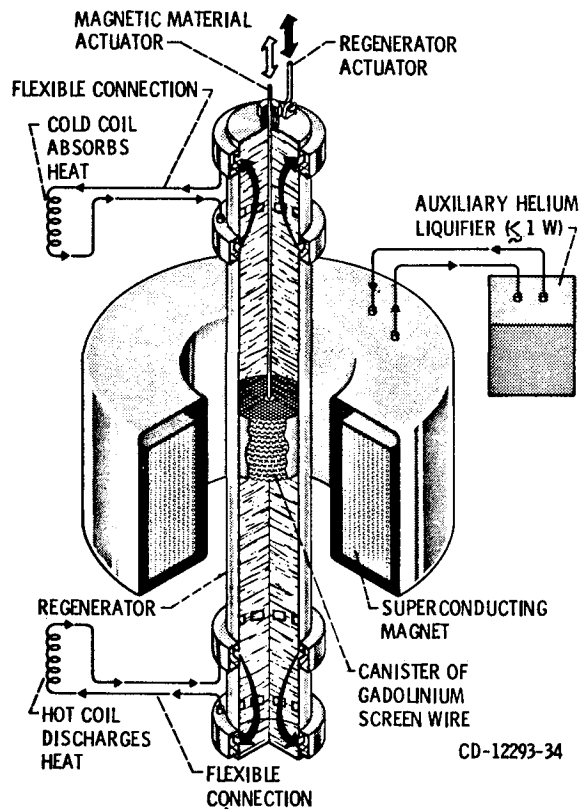


Figure 3

Long-Life Cathodes and Traveling Wave Tubes

Joseph N. Sivo

The high-power, high-efficiency traveling wave tube is of significant importance in our deep space and synchronous orbit communication efforts. The cathodes and depressed collector are crucial to the long life and efficiency of the tube.

Matrix Cathodes

Thermionic cathodes are electron-emitting devices that operate at high temperatures ($>750^{\circ}\text{C}$). They are essential in microwave electron tubes and are the ultimate cause of failure. Therefore high-electron-current-density cathodes with long life are a vital requirement. Present and future interest in high-power millimeter-wave tubes has generated a need for thermionic cathodes that will develop current densities greater than 1 A/cm^2 and have lives longer than 5 years. The matrix cathode called the M-cathode should satisfy this application.

To confirm the superior characteristics of the M-cathode over commercial cathodes, Lewis supported a life test program that competitively evaluated matrix cathodes. In this life test the cathodes were tested in their normal-use environment. To do this, a traveling wave tube (TWT) type of test apparatus was used. The cathode was mounted in an electron gun structure, and the electron beam generated was magnetically focused through a tunnel-like structure similar to a TWT and dissipated in a water-cooled collector at the end of the tube (fig. 1).

The results of this life test study are shown in figure 2. The S- and B-cathodes are tungsten-impregnated matrix cathodes that differ mainly in the content of the barium impregnant mix. The M-cathode is essentially a B-cathode that has a sputtered osmium coating on its surface. The current degradation with time for the S- and B-cathodes, with the anode voltages fixed, is characteristic of tungsten-impregnated cathodes without an osmium coating. The B-cathode is better than the S-cathode. However, the M-cathode shows no degradation after 4 years and has superior characteristics. An additional advantage of the M-cathode is that it runs at an operating temperature 90 to 100 degrees C lower than either the B- or S-cathode and still delivers high emission current under stable conditions.

Field Effect Cathodes

Cathodes are normally thermionic emitters that operate at high temperatures in order to achieve high electron current densities. Operation at high temperatures tends to limit the life of the device and to lead to stability and reproducibility problems. Tube designers and users would like electron emitters that run cold or at relatively low temperatures. Recently such a cathode has been developed under NASA sponsorship. The cathode is a cold cathode that operates as a thin-film field effect cathode (TF FEC)(fig. 3). It is made by techniques similar to those employed by the semiconductor industry. The surface of silicon substrate is oxidized and coated with a thin film of molybdenum. By electron lithography, holes are made in the molybdenum surface, separated by about $12\text{ }\mu\text{m}$ and extending through the SiO_2 insulating layer. Molybdenum cones are then sputtered into the holes,

with the resulting structure shown in figure 3. A scanning electron microscope photograph of one of the points is shown at the bottom of figure 3.

Cathodes developed with this technique have 5000 points in a 1-mm-diameter area. A small portion of such a cathode is illustrated by the scanning electron microscope photograph shown in figure 4. Electron emissions from these cathodes are obtained by applying a positive gate-to-cone voltage, which results in electric fields at the cone point. These strong electric fields cause copious electron field emission from the cone tips. Such field effect cathodes (FEC) can deliver electron currents of 100 mA, which is equivalent to 13 A/cm^2 . Currents of this magnitude are much higher than those obtainable from thermionic cathodes. Further developments in FEC's have shown that current densities of 50 to 100 A/cm^2 are feasible. Cathodes with such high current densities are important for future developments in microwave tubes.

Multistage Depressed Collectors

The multistage depressed collector (MDC)(fig. 5) is used to recover a large part of the residual kinetic power of spent electron beams emerging from the exits of linear-beam microwave tubes and thus to substantially increase the overall system efficiency.

Maximizing overall efficiency is of importance for space, airborne, and high-power applications because the overall efficiency has a direct bearing on the size, weight, and complexity of the prime power, power conditioning, and heat rejection systems. Therefore the most important potential applications of the MDC are in microwave amplifiers for space communications, in traveling wave tubes used in airborne electronic countermeasure (ECM) systems, and in high-power tubes used in ultra-high-frequency (UHF) television stations and radar units.

To date, the MDC's have been used in communications satellites and in a number of airborne ECM systems. They have great economic application to UHF television klystron transmitters (of which 1100 are presently in operation in the United States and 2000 are expected by the year 2000).

CATHODE INSTALLED IN LIFE TEST SECTION

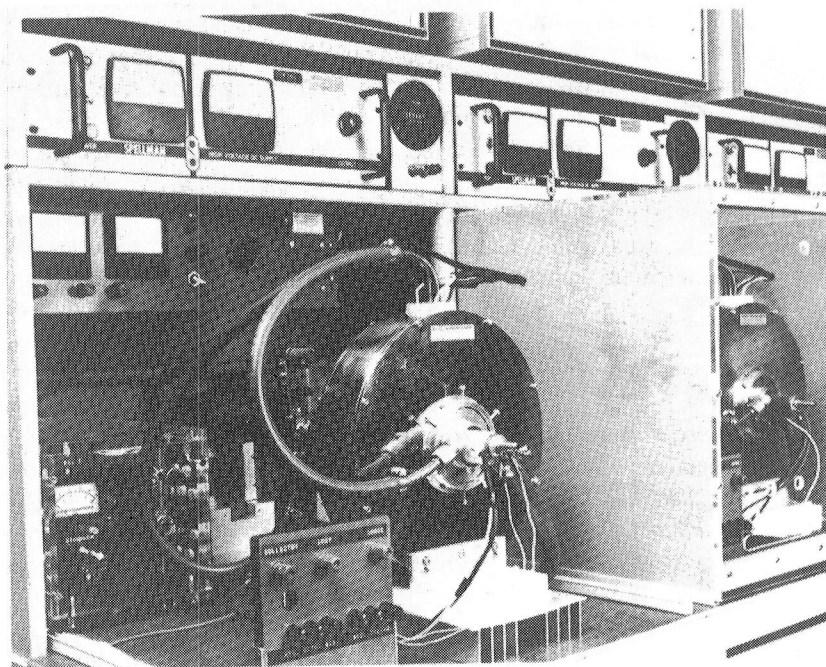


Figure 1

CATHODE CURRENT AT FIXED ANODE REFERENCE VOLTAGE VERSUS TIME

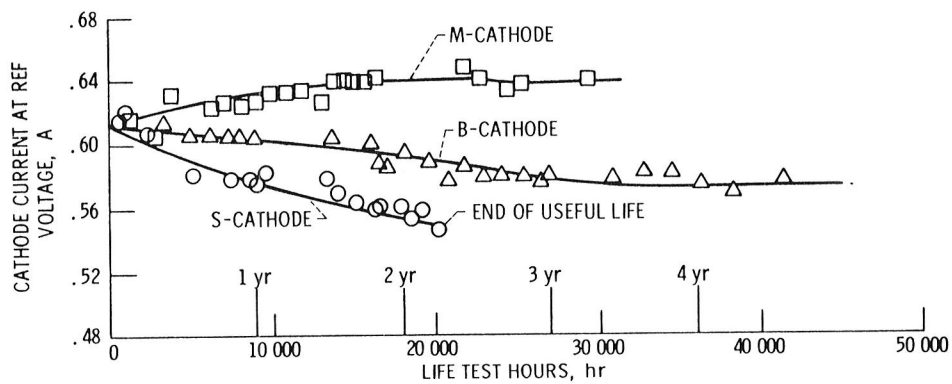


Figure 2

SCHEMATIC DIAGRAM AND SCANNING ELECTRON MICROGRAPH OF THIN-FILM FIELD EMISSION CATHODE

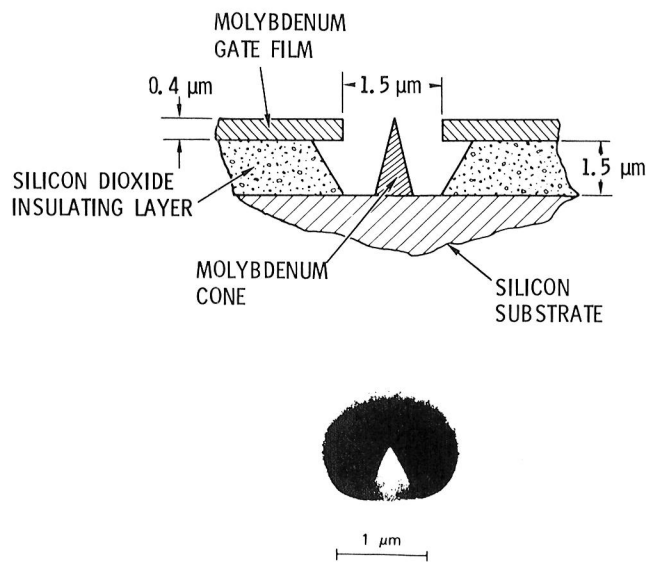


Figure 3

SEM PHOTOGRAPH OF SMALL PORTION OF TFEC CATHODE

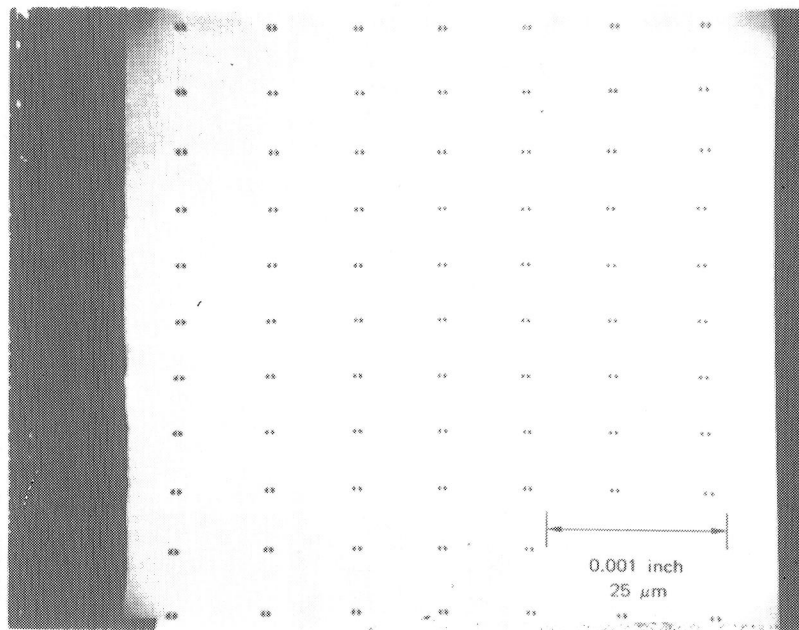
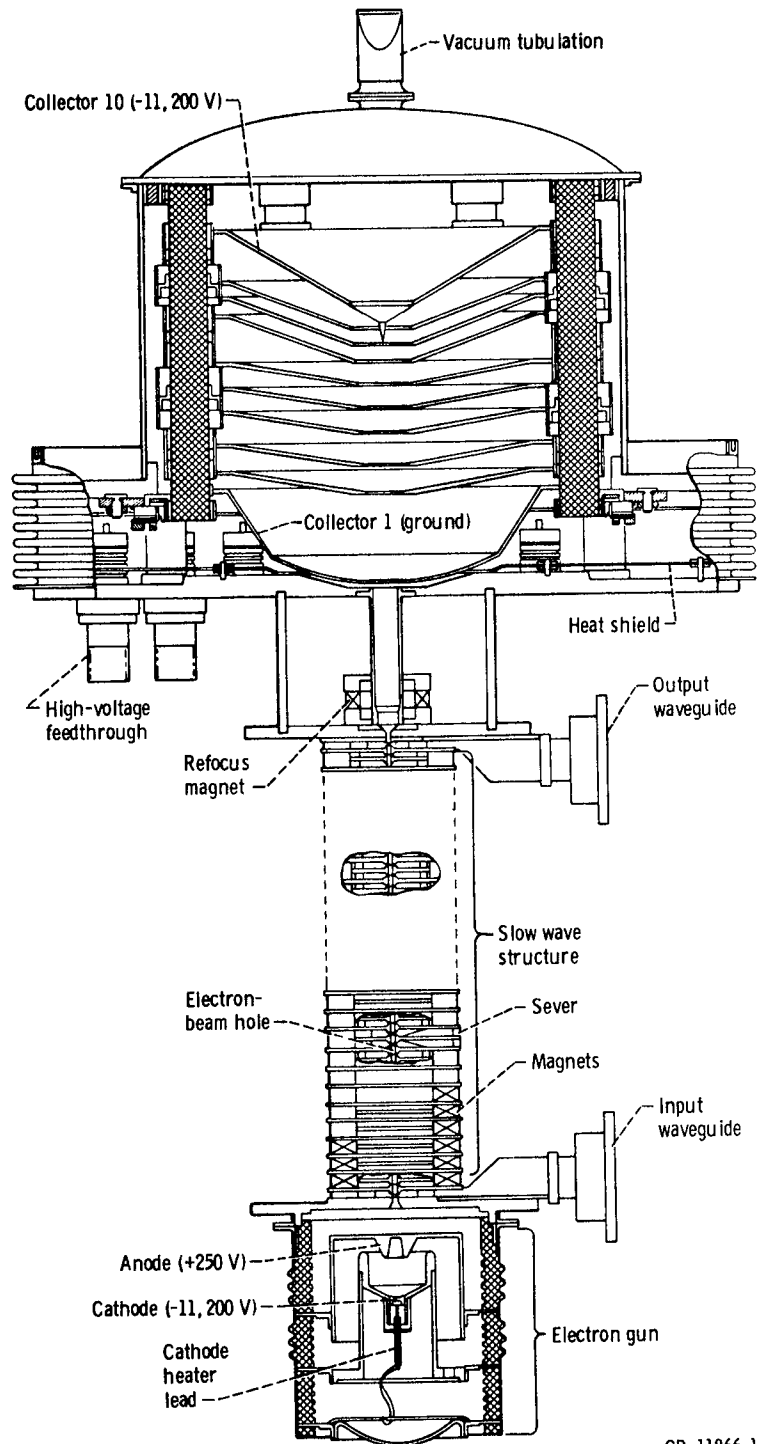


Figure 4

COUPLED-CAVITY TRAVELING WAVE TUBE WITH MULTISTAGE DEPRESSED COLLECTOR



CD-11866-17

Figure 5

Nasvytrac—High-Performance Multiroller Traction Drive

Stuart H. Loewenthal

Technology is being developed at the NASA Lewis Research Center on high-performance traction drives. The Nasvytrac traction drive transmits power between lubricated, smooth rollers under compression without the aid of gear teeth. Compared with gear drives, the Nasvytrac transmission can handle power in a more compact, lightweight package and is much quieter. A quieter transmission would be particularly advantageous for civilian helicopter applications, in which present geared transmissions generate considerable cabin noise. Helicopter test transmissions based on the Nasvytrac principle are currently being prepared for testing.

Figure 1 shows the roller-cluster planetary configuration of a 15:1-constant-ratio, 200-horsepower test drive. The sun and ring rollers are connected to shaft members (not shown) and act as the input or output elements. The drive functions equally well as a speed reducer or increaser. Most conventional geared systems have speed ratios limited to about 10:1 per stage, but the Nasvytrac system can readily be designed for ratios of 150:1 in a single stage. Unlike many multistage geared systems and geared differentials, the efficiency of this transmission will not be significantly degraded with increases in the required speed ratio. Peak overall drive efficiency of about 95 percent has been measured on these units.

TRACTION DRIVE GEOMETRY

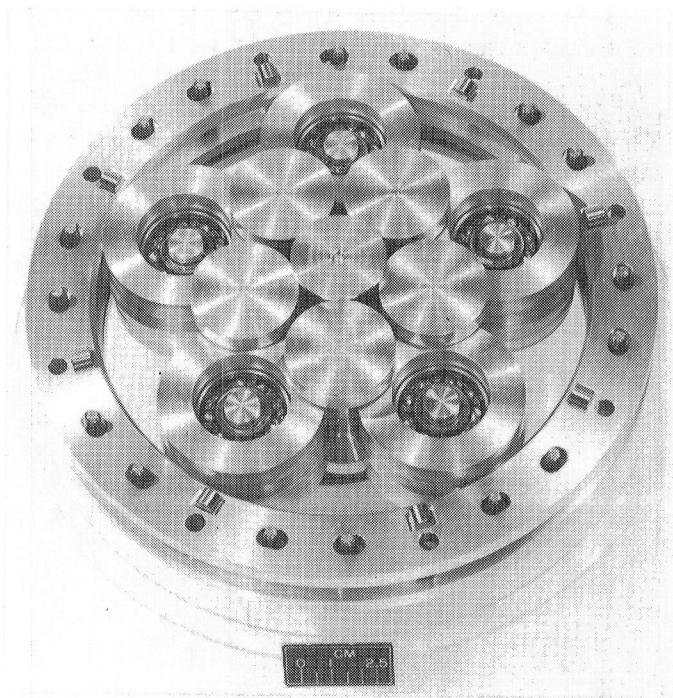


Figure 1

EXAMPLE OF TRACTION DRIVE SIZES

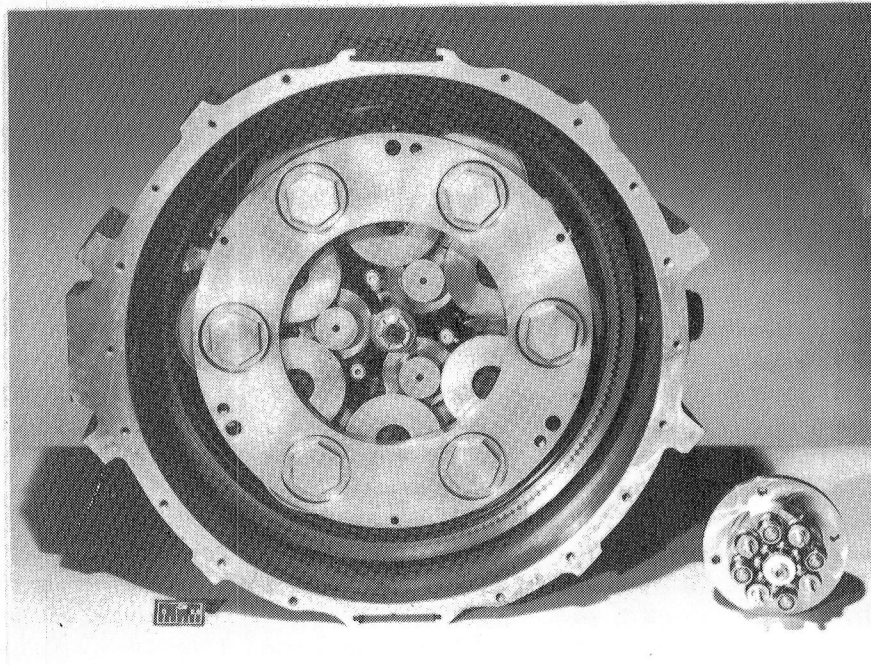


Figure 2

Because it does not have speed-limited gear teeth, the practical speed limit of the drive is dictated only by the mechanical equipment to which it is attached; one demonstrated drive runs in air, without lubrication, at speeds to 180 000 rpm. The drive can be built in small and large sizes as shown in figure 2. The small drive is a 30-horsepower, 3.25:1-ratio drive for a rocket engine turbopump; it weighs just 9 pounds and runs at input speeds of 95 000 rpm. The larger drive transmits 500 horsepower, has a ratio of 48:1, weighs 210 pounds, and runs at input speeds of 53 000 rpm.

The Lewis Research Center is currently investigating applications of the traction drive unit as an engine speed reducer for automotive gas turbines and as a speed increaser for wind turbine generators. Potential industrial applications for textile machinery, conveyor equipment, and machine tools are being studied by NASTEC, Inc., a Cleveland-based company responsible for the commercialization of this device.

The simpler, lighter, and potentially less expensive Nasvytrac drive appears to be an excellent replacement for geared speed changers for many applications.

General-Aviation Aircraft Engines

Edward A. Willis, William J. Rice, Michael Skorobatchky,
Robert A. Dezelick, and Philip R. Meng

Progress is being made in improving spark ignition engine technology and in key technologies for turbocharged diesel engines and rotary engines that offer promise of light weight and high fuel efficiency. A number of broadly useful experimental techniques accompany this work. Transfer of the results and methods to ground-based applications seems probable.

Engine Diagnostic Instrumentation

Present research at Lewis for improved fuel economy and decreased emissions for general-aviation light aircraft engines has necessitated the development of improved engine diagnostic instrumentation. These instruments were all designed and developed and prototypes made at Lewis. Additional units were fabricated in convenient modules for Lewis by small businesses in the Cleveland area. This system (fig. 1) has the capability to measure and compute combustion

MODULAR ENGINE INSTRUMENTATION SYSTEM

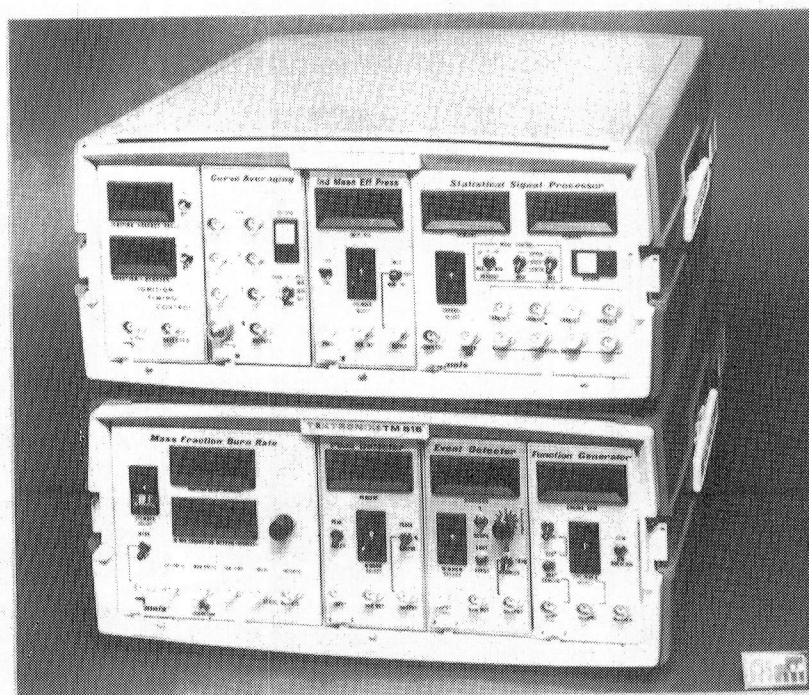


Figure 1

parameters on a cycle-by-cycle basis in real time at engine speeds up to 6000 rpm. In addition, these data are reduced to the statistical parameters (mean; standard deviation) and to histograms or bargraphs.

Some of the functions of this system are depicted in figure 2. This pressure-volume diagram, or indicator diagram, is a two-variable plot of combustion pressure and cylinder volume. The area enclosed by the diagram is a measurement of the work done at the piston face for one combustion cycle. When this work is divided by the displacement volume, the result is called indicated mean effective pressure (IMEP), an important combustion parameter.

The rates at which fuel is burned during the combustion process for three different air-fuel ratios are shown in figure 3. The data in the example show increasing time required for the fuel to burn completely as the engine is "leaned out" (higher air-fuel ratios). If the mixture is too lean, the fuel never does burn completely and produces undesirable emissions in the exhaust.

Bargraphs of IMEP for six engine operating conditions are shown in figure 4; each bar is for a single engine cycle. Bars extending upward from the zero line represent negative work. Each set of bargraphs is for one of the cylinders and for 100 consecutive engine cycles, with the first cycle represented by the leftmost bar and progressing to the right for successive cycles. Some idea of the usefulness of this information is illustrated for the six examples.

The first bargraph is for an engine startup. The first few bars are negative while the engine is being cranked; then the engine goes into an idling condition. The second bargraph is for a smoothly idling engine. Even though this is a well-tuned engine, approximately 40 percent of the combustion cycles are total or partial misfires. This occurrence is typical for all spark-ignited engines.

The next four bargraphs depict a steady 55-mph road load condition for different equivalence ratios. At an air-fuel ratio (A/F) of 15, $\phi = 1.0$; at an A/F of 17.5, $\phi = 0.81$; at an A/F of 18.5, $\phi = 0.77$; and at an A/F of 19.5, $\phi = 0.66$. Even though the engine is doing the same amount of work in all four cases, it is doing it in a less satisfactory fashion as the engine is leaned out, that is, more cycle-to-cycle variations, increasing misfires, and uneven performance among cylinders.

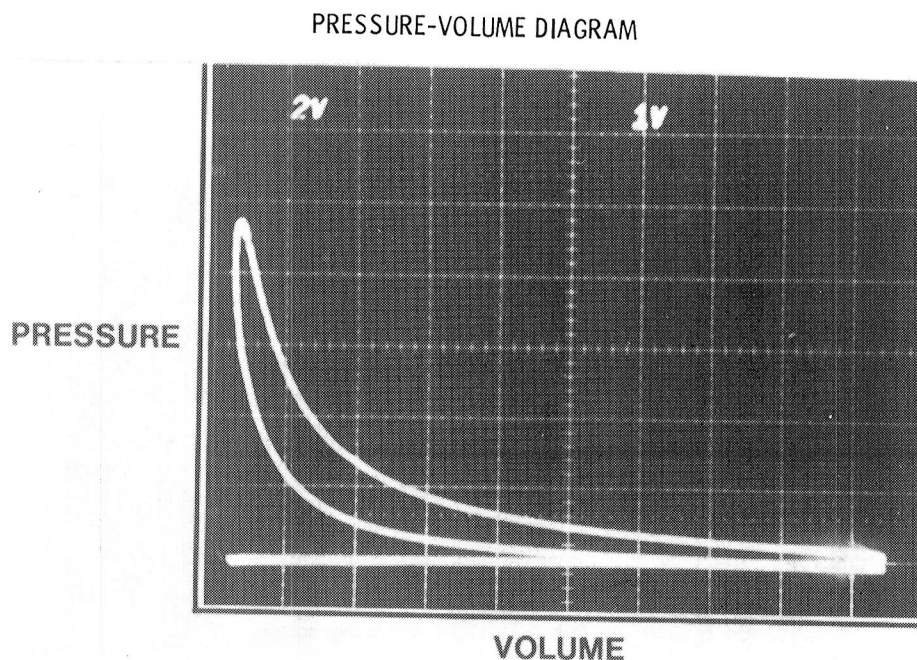


Figure 2

FUEL BURNING RATE CURVES

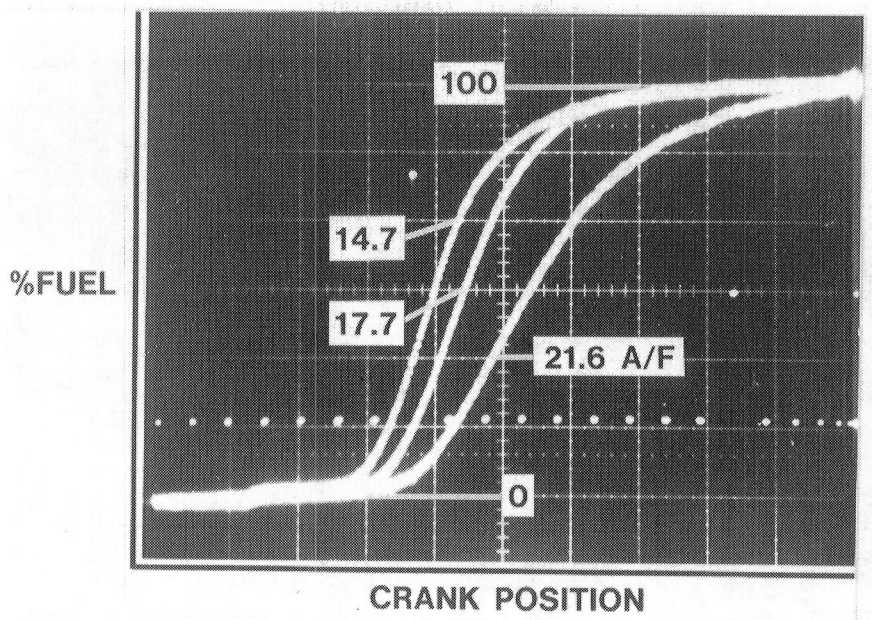


Figure 3

Piston Engine Research

A Teledyne Continental Motors general-aviation spark ignition piston engine (GTSIO-520-F) is depicted in figure 5. This geared, turbosupercharged, fuel-injected, six-cylinder horizontally opposed, air-cooled engine typifies the engines that power 93 percent of all general-aviation aircraft, that is, more than 170 000 aircraft. Such engines have served this industry well for over 30 years and have been gradually improved to very creditable levels of performance and reliability. Since this is the prevalent type of general-aviation engine, new technology to improve it will potentially benefit the whole fleet.

In recent years the fuel crisis and inflation have contributed to continuing problems in the availability and cost of general-aviation gasoline. Therefore, for this engine to be a viable powerplant in the future, it must have multifuel capability (gasoline and jet/diesel), reduced fuel consumption, higher altitude capabilities, reduced weight and cooling drag, and digital electronics for controls and thus improved reliability. Durability and maintainability are also highly desirable.

A number of technical areas for improving the spark ignition piston engine are under study both at Lewis and by contractors. Lewis contractors are working on high-turbulence combustion chambers, stratified-charge combustion chambers, turbochargers and turbocompounding systems, exhaust valves, low-drag cylinder heads, multiroller traction drive, and weight reduction with materials such as light metals and graphite-reinforced plastics.

Lewis is working on fuel systems and fuel injection and is using several novel techniques to observe fuel sprays and their effects on combustion. For example, fiber optics and high-speed photography permit examination of the fuel injection process through a Lucite inlet port (fig. 6). Figure 7 shows operation of an air-atomizing, continuous-injection fuel nozzle of the type presently used in aircraft engines. The extreme operating conditions of idle (600 engine rpm) and takeoff (2800 engine rpm) are illustrated. At idle, with low manifold pressure and a large air pressure drop through the nozzle, the fuel is injected as a liquid stream. The insight gained from photography of sprays has been applied to measurements of both the fuel-air mixtures in the combustion chamber and combustion

HISTOGRAMS OF ONE CYLINDER OF ENGINE

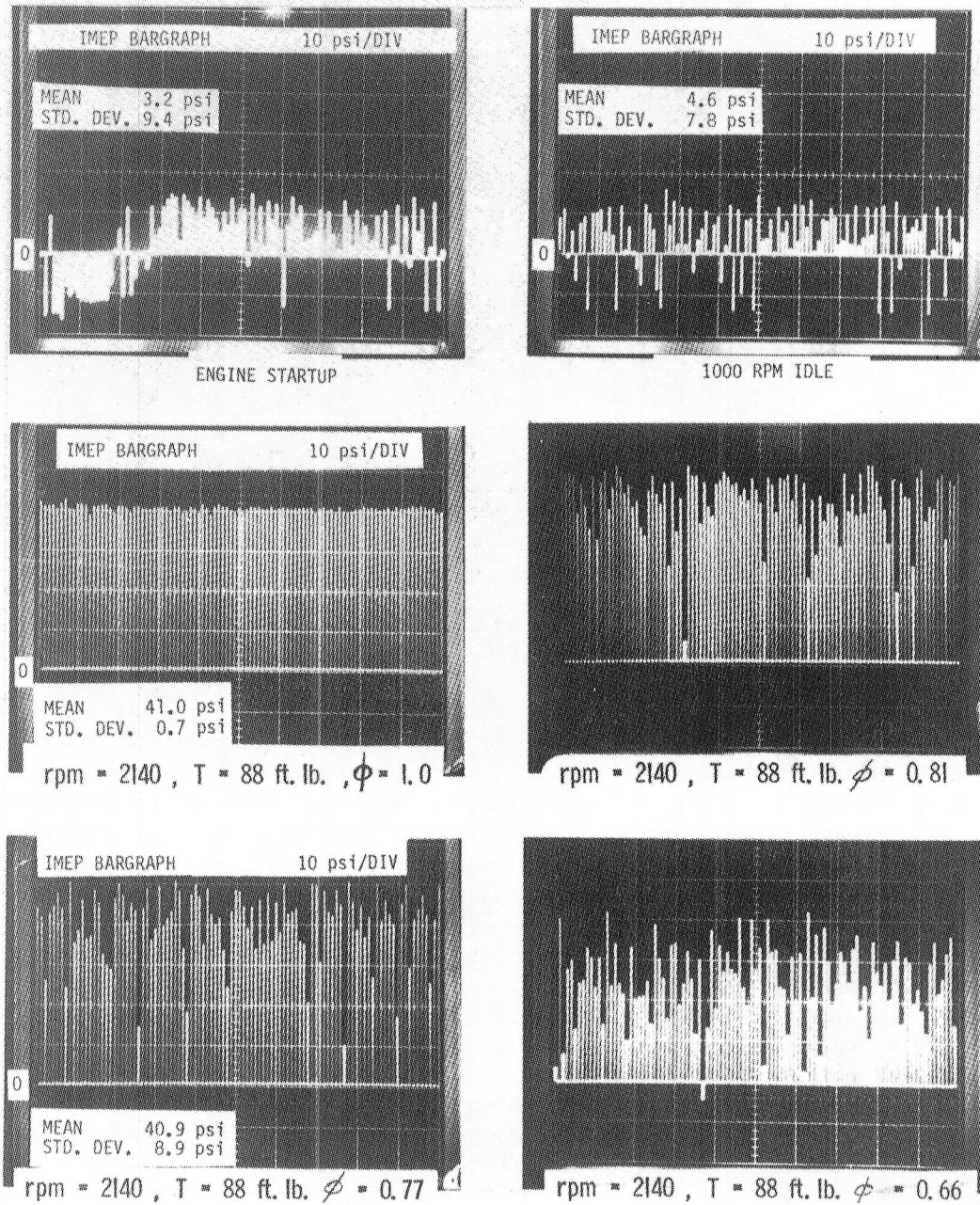


Figure 4

GENERAL-AVIATION SPARK IGNITION ENGINE

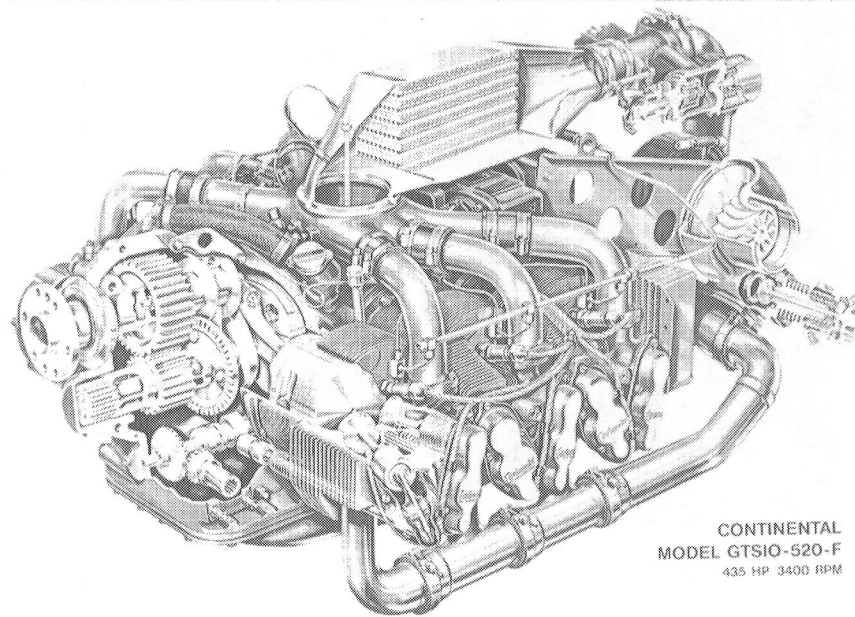


Figure 5

CYLINDER HEAD WITH TRANSPARENT INTAKE SECTION

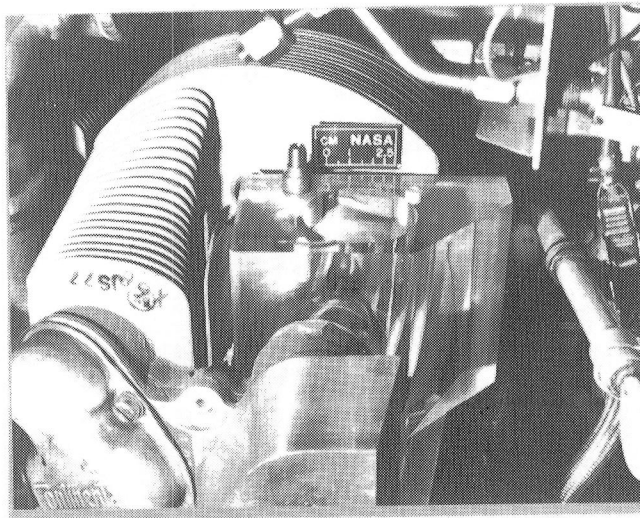


Figure 6

FUEL SPRAY

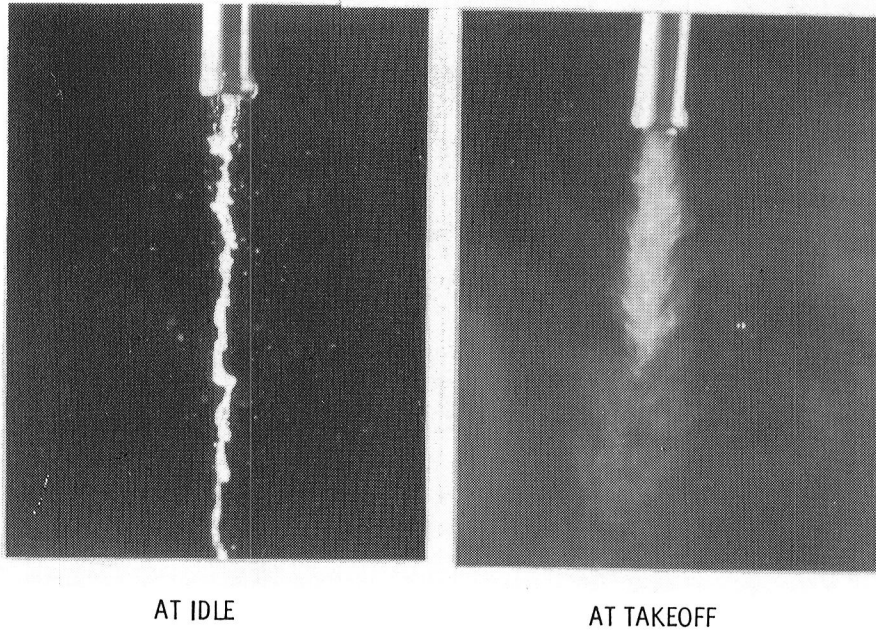


Figure 7

performance. Figure 8 shows a gas sampling valve used for measuring fuel-air ratio. Combustion performance is deduced from cycle-by-cycle measurements of cylinder pressure and volume.

Recently, under contract, Lewis has demonstrated on an experimental spark ignition piston engine improvements in fuel economy of 10 percent in cruise performance and up to 30 percent in the landing-takeoff cycle. This technology, if applied to the entire general-aviation piston engine fleet, would theoretically save 10 to 30 percent of our total general-aviation gasoline consumption. Since

GAS SAMPLING VALVE INSTALLED IN CYLINDER HEAD

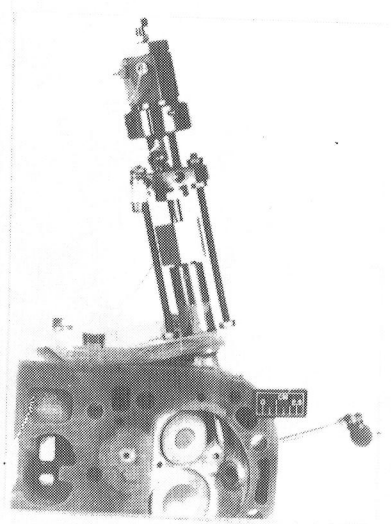


Figure 8

this is presently a \$1-billion-per-year market, the annual savings potential is \$100 million to \$300 million in total, or an average of \$600 to \$2000 per year to each airplane owner.

Diesel Engine Research

Since about 1930, diesel engines occasionally have been used in aircraft; but for various reasons, such as excessive weight, they have not been widely accepted. A recent study conducted for NASA by Teledyne Continental Motors, General Products Division, produced the concept shown in figure 9, a two-cycle, radial, turbocharged diesel engine. The diesel engine has excellent fuel economy and is well known as a reliable and very durable engine. It is also lean burning and uses lower cost fuel than a spark ignition engine. Note that with the two-stroke cycle engine, the valve train and ignition system have been eliminated. Some of the future needs for aircraft service are inherently satisfied in this particular design. The radial configuration is compact and lightweight and could be cheaper. The turbocharger provides high-altitude capability and improved specific fuel economy.

A number of specific technical advances are needed if the diesel engine is to see future service for aircraft. For fuel injection the most important advance would be programmed fuel delivery. The most important advance for turbocharger technology would be variable-area turbines and single-stage compressors, with pressure ratios up to 8 or 9. The turbocharger shown in figure 10 is of the simplest type. That is, the compressor, on the same shaft as the turbine, provides air directly into the cylinder; exhaust gases drive the turbine. The same shaft can also drive an oil pump and alternator.

Alternative systems are being studied. For example, a combustor in the exhaust line ahead of the turbine can drive the compressor independently of the engine. The alternator on the same shaft as the turbine and compressor is also used as a motor to start the system. The turbocharger can then operate as an auxiliary power unit. Several possible advantages might accrue from this system. The unit could

GENERAL-AVIATION DIESEL ENGINE

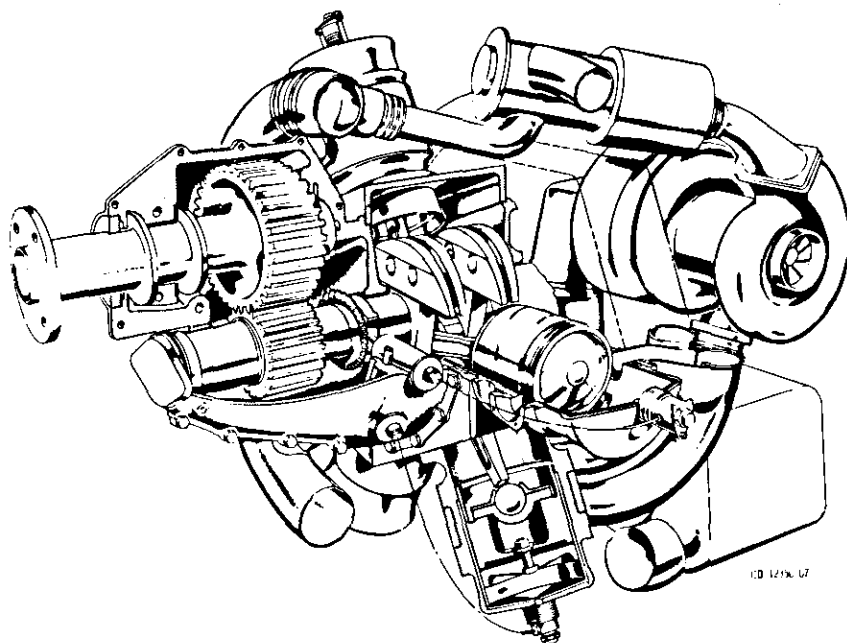


Figure 9

GENERAL ARRANGEMENT OF AIR AND EXHAUST GAS SYSTEM

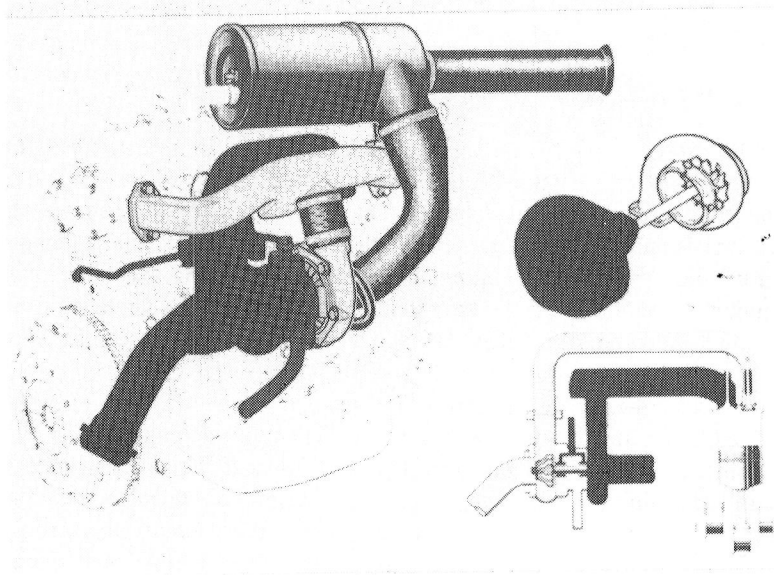


Figure 10

provide air-conditioning for the pilot on the ground without the engine running; also, a lightweight air turbine starter could eliminate the electric starter and reduce the battery load requirement. The engine could also be warmed up for easy starting in cold weather by directing the hot air through the engine.

Lewis is working toward an “adiabatic” diesel engine in which the interior of the combustion chamber is insulated to reduce heat losses to the cooling system. Figure 11 shows the items that would be insulated in a turbocompounded, adiabatic diesel engine. Turbocompounding, where a turbine is

ADIABATIC DIESEL ENGINE

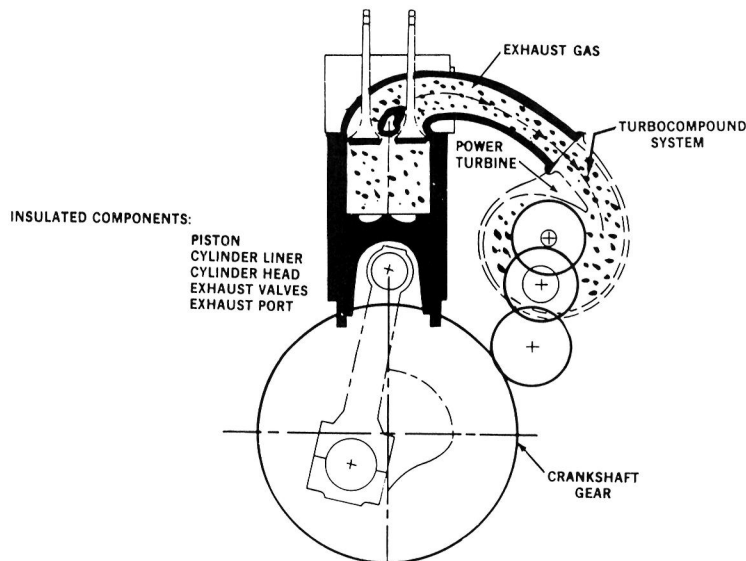


Figure 11

geared to the crankshaft, is another means of extracting additional work from exhaust gases. The insulated components direct the heat, formerly lost to the cooling system or to the exhaust, to be captured as useful work. The items that would be insulated or coated to reduce heat transfer are the piston, the cylinder liner, the cylinder head, the exhaust valves, and the exhaust port. Insulation should keep the heat away from the oil and keep it from moving through the walls of the engine. The resulting smaller oil coolers and less airflow for cylinder cooling would be reflected in lower weight and reduced cooling drag, both important attributes for an aircraft engine.

Consider the gains that are being sought. Figure 12 shows that in a basic nonturbocharged engine the energy available in the fuel is distributed as follows: approximately 33 percent in losses to the coolant, 33 percent to the exhaust, and 33 percent to brake horsepower. With turbocharging and turbocompounding the energy going into brake horsepower is about 41 percent. With the adiabatic, turbocharged and turbocompounded engine the brake horsepower is about 48 percent of the supplied energy, and the cooling losses are down to about 17 percent.

ENERGY BALANCE COMPARISON FOR DIESEL ENGINE

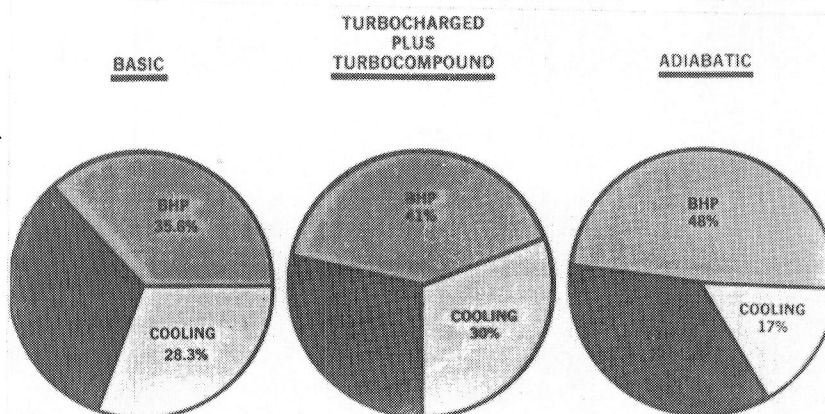


Figure 12

Rotary Engine Research

The rotary engine—inherently compact, lightweight, and smooth running—is a candidate for use in general-aviation aircraft. Shown in figures 13 and 14 are mockups of recent rotary engine designs being studied for light aircraft by Curtiss-Wright Corp. under a NASA contract. The single-rotor, advanced RC1-75 (fig. 13) delivers 300 hp at sea level and 250 cruise hp at 25 000 feet. The dual-rotor RC2-75 (fig. 14) delivers 600 hp at sea-level takeoff and 500 cruise hp at 25 000 feet. Both have good fuel economy. These stratified-charge, multifuel engines can operate on jet fuel, aviation gasoline, or mixtures thereof. The RC2-75 has a very desirable specific weight (lb/hp) of only 0.81. Rotary engines are relatively simple and are mass producible. Technology work is directed at better fuel economy, increased power density, longer seal life, and better high-altitude capability.

A large ground vehicle engine designed and presently being developed by Curtiss-Wright Corp. under a U.S. Marine Corps contract is shown in figure 15. This stratified-charge engine is rated at 1500 hp at 3600 rpm and has four rotors, each with 350-in³ displacement. The engine designed with case and eccentric shaft separation through the center can be used as 2 two-rotor engines of 750 hp each. The engine has multifuel capability (gasoline, diesel fuel, or JP-4). This naturally aspirated engine weighs 1860 pounds in the four-rotor version. With turbocharging the horsepower could be

SINGLE-ROTOR GENERAL-AVIATION ROTARY ENGINE

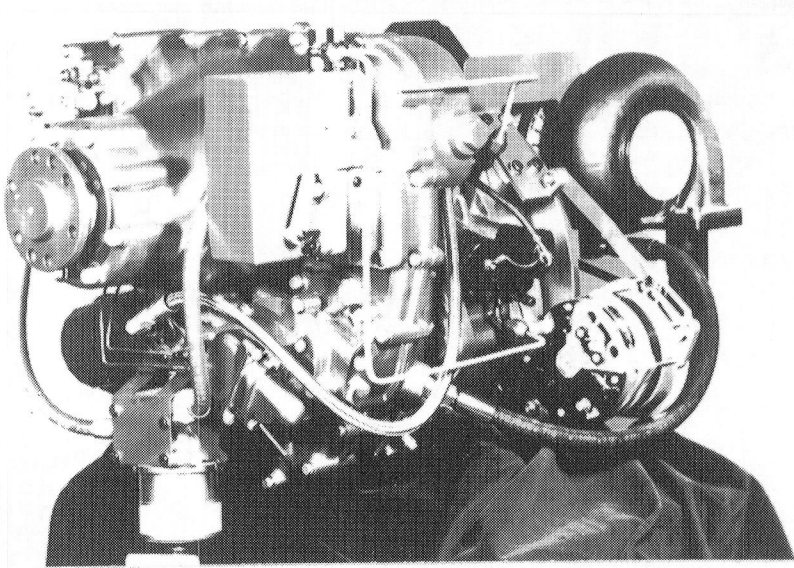


Figure 13

DUAL-ROTOR GENERAL-AVIATION ROTARY ENGINE

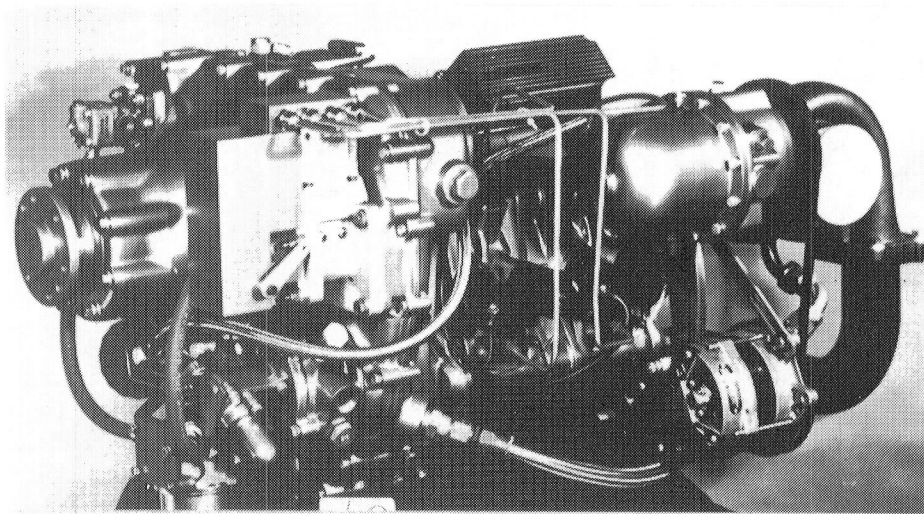


Figure 14

increased from 1550 hp to 2500 hp (the range for commuter aircraft), with only a slight increase in overall weight.

The Lewis rotary engine work is being accomplished both on contract and by in-house research. For the in-house research Mazda automotive rotary engines are used because both the engines and replacement parts are readily available and inexpensive. A cutaway view of a rotary engine with the technology items numbered is shown in figure 16. The technology items are (1) Kistler pressure transducers, (2) ceramic-coated steel or fiber-reinforced plastic rotors, (3) seals, (4) fuel-injection

ADVANCED GROUND VEHICLE ENGINE

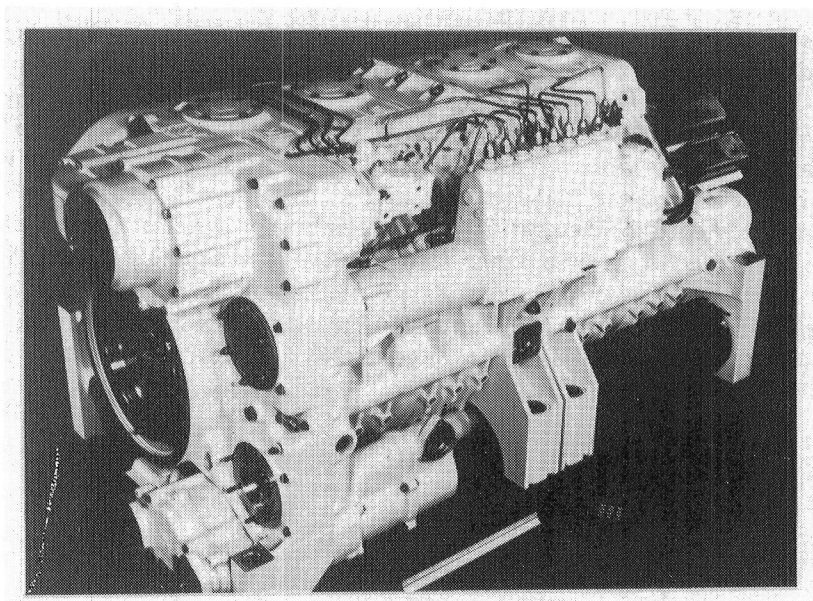


Figure 15

ADVANCED-TECHNOLOGY ITEMS

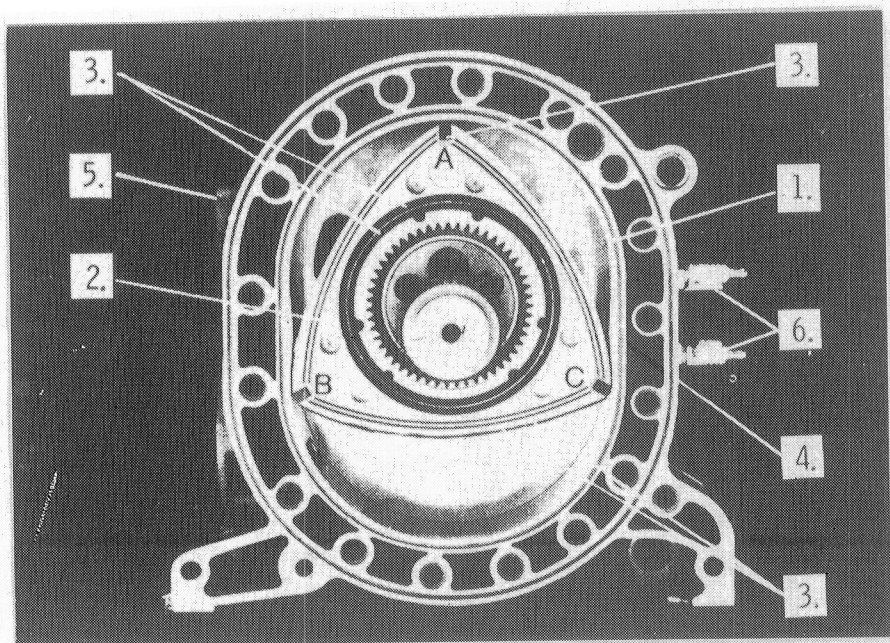


Figure 16

systems, (5) turbocharger systems and controls, and (6) high-energy ignition systems and electronic controls. Kistler pressure transducers are installed through the housing at four locations so that a continuous pressure trace of the engine cycle can be made while it is running. Existing steel rotors are to be insulated with a ceramic coating on the combustion surfaces of each rotor face. A second method is to completely replace the steel rotors with fiber-reinforced plastic rotors that have a ceramic coating on the combustion surfaces. These insulation methods will reduce heat transfer to the engine oil and thus allow more combustion energy to go to power. Seals require work to advance their technology because of the higher speeds and loads required. Better, faster operating fuel injection systems are needed for the stratified-charge combustion systems. Turbocharger systems and better controls are needed to increase power density and to provide altitude capability. High-energy ignition systems and digital electronic controls are needed for the lean mixtures in the stratified-charge combustion system. The combined effects of these advances should produce a very desirable high-performance powerplant for future use in general-aviation aircraft.

Redox

Laurence H. Thaller

Redox (reduction/oxidation) is a unique electrochemical energy storage system. As does a battery, it stores electric energy and releases it on demand. The system (fig. 1) converts chemical energy to electric energy by flowing two reactant fluids past opposite sides of an ion exchange membrane. These anode and cathode fluids (e.g., chromium chloride and iron chloride) are stored in separate tanks, and both the flow and the chemical reaction are fully reversible to provide discharge-recharge cycles. System energy storage capacity is determined by the quantity of fluids (tank sizes), and energy output rate (power) is determined by the number of flow cells (fig. 2) in the system. A complete system (fig. 3) includes a cell that monitors system charge and a rebalance cell for correcting minor side reactions.

Extensive research and laboratory and technology development work have been completed. A 1-kilowatt operating system is in test and experimental use at Lewis, and a program of multikilowatt demonstration units is scheduled as a means of transferring the technology to industry.

Redox energy storage uses available materials and simple components and promises to provide inexpensive systems with very long life and reliable, low-maintenance operation. Because storage capacity and power output are separately determined and sized, the system is highly flexible and versatile and can be adapted readily to a variety of operation requirements.

Redox systems—because of their low cost, flexibility, reliability, and long life—offer substantial advantages in energy storage for use with solar photovoltaic and wind energy electrical generation systems. Those same characteristics make redox systems suitable for bulk energy storage by electric utilities. Redox storage of the baseload generating capacity would be used to reduce or eliminate the use of oil- and gas-fired peaking and intermediate load generators. An artist's sketch of a 10-megawatt (rate), 100-megawatt-hour (capacity) utility storage system is shown in figure 4. Redox may also be used by large electricity consumers (e.g., basic metals producers) so that they could buy off-peak power at preferred rates for storage and later use, both to reduce costs and to improve supply reliability.

PRINCIPLE OF OPERATION OF NASA REDOX CONCEPT

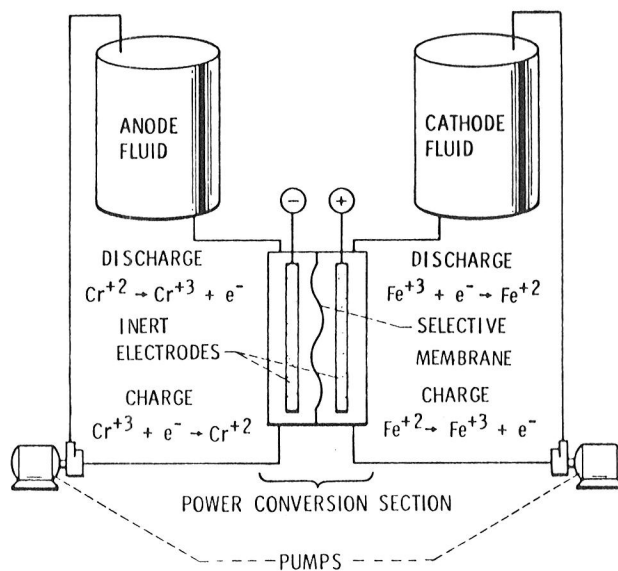


Figure 1

REDOX STACK AND SINGLE-CELL COMPONENTS

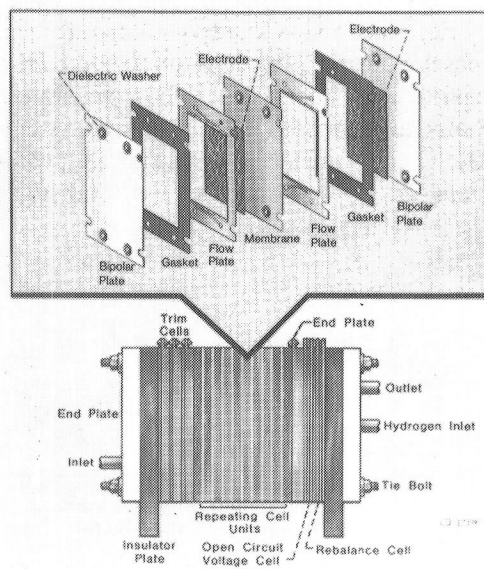


Figure 2

FULL-FUNCTION NASA REDOX ENERGY STORAGE SYSTEM

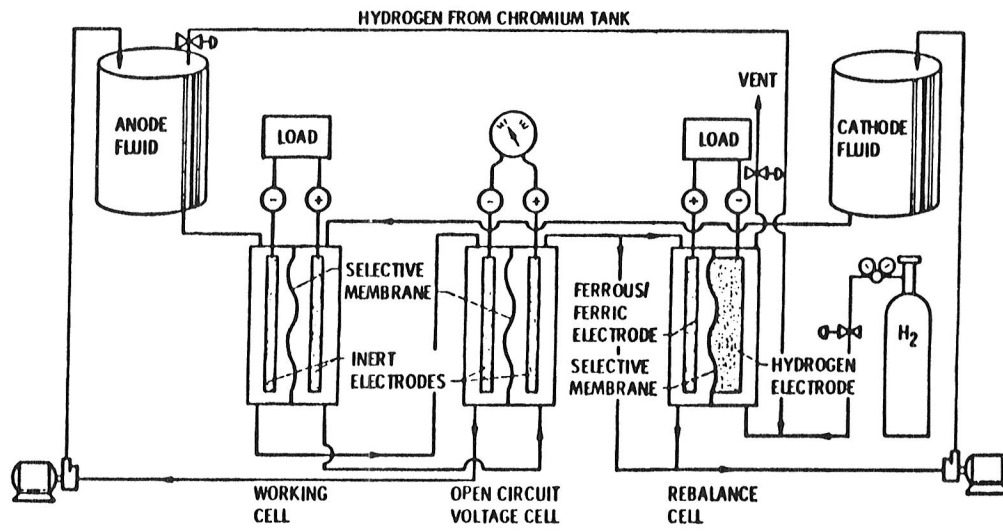


Figure 3

ELECTRIC-UTILITY-DISTRIBUTED ENERGY STORAGE SYSTEM

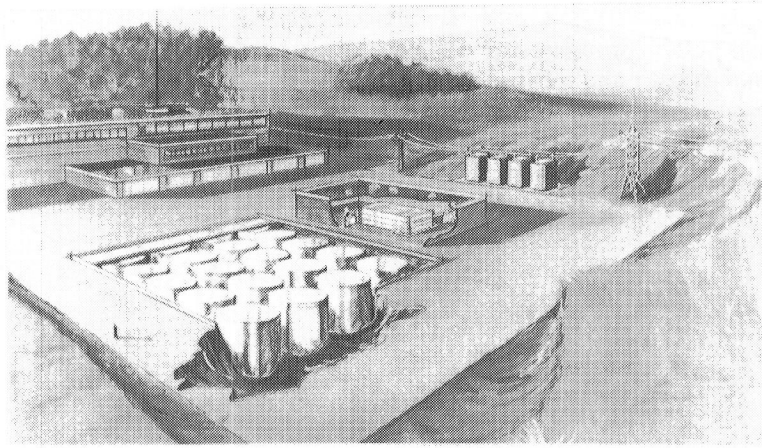


Figure 4

Laser Applications to Measurement Systems

**John P. Barranger, Arthur J. Decker, J. Anthony Powell,
John L. Pollack, and Norman C. Wenger**

The Lewis Research Center uses lasers in several measurement systems in order to understand better the operation of advanced turbine-engine components. Laser light allows the measurement of phenomena without disturbing the phenomena being measured and can make measurements in hostile regions where other measurement systems using physical probes are unacceptable.

High-Speed Laser Anemometer System

To verify analytical design equations, measurements must be made of the airflow velocity within research compressor rotors while they are spinning at design speeds up to 16 000 rpm. Physical probes cannot be used. The laser anemometer (refs. 1 and 2) presently provides the only practical solution to this difficult measurement problem. When two laser beams of the same frequency intersect, they interact to form interference fringes—a series of light and dark planes within the small intersecting “probe volume.” The probe volume is located in the region where measurement is desired, and very small particles are introduced into the flow so that they pass through this volume. Each time a particle passes through a bright fringe, it scatters light in all directions. The anemometer detects these flashes of light and measures the time between flashes. The distance between fringes is known precisely. Knowing the time and the distance, we can calculate the velocity of that particle, and this gives a measure of the airflow velocity at a particular point within the rotor. This measurement process takes about a millionth of a second and occurs thousands of times a second at different positions of the rotor as it spins.

Figure 1 shows the laser beam path through the optics. The single beam is split into two separate beams that enter the compressor through a window in the casing and intersect at the measurement point within the rotor blade row.

Laser-Optical Blade Tip Clearance Measurement System

In advanced-technology turbine engines avoiding loss through leakage flow from excess blade tip clearance is important, but insufficient initial clearance can cause interference problems during operation. A previous system (ref. 3) measured the average blade tip clearance over several rotor revolutions but could not measure transient or single blade tip clearance. A new laser-optical measurement system (refs. 4 and 5), designed and built by Pratt & Whitney Aircraft under contract, measures single and average blade tip clearances between a rotor and its gas path seal in turbine engine components (fan, compressor, and turbine) and in complete engines.

The measurement system (fig. 2) has optical, electronic, and computer-graphic subsystems. The engine-mounted probe operates in the turbine environment. This system has a number of innovative features that combine optical, electro-optical, electronic, and computer-graphic elements and is

LASER ANEMOMETER OPTICS SHOWING LASER BEAMS

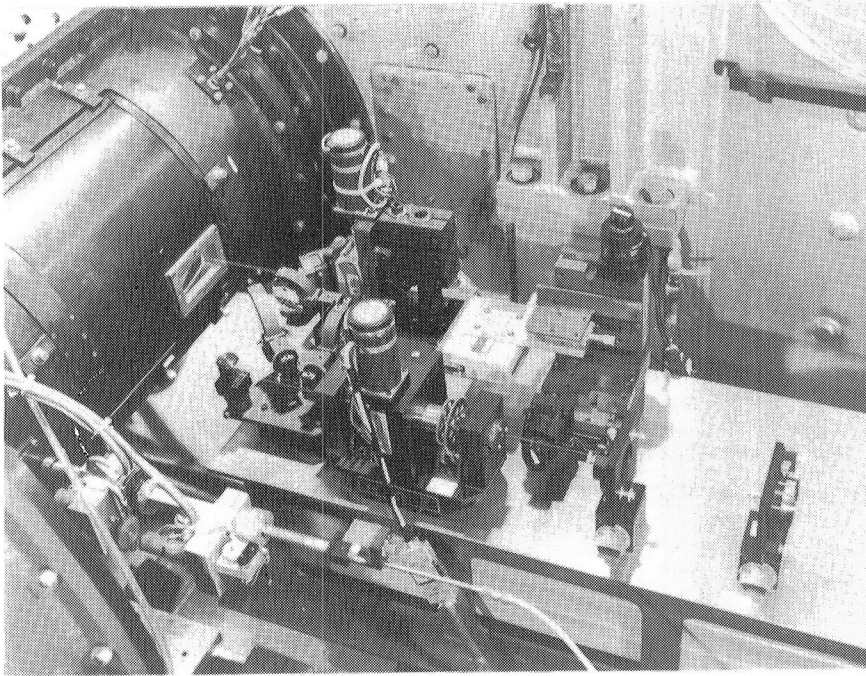


Figure 1

BLADE TIP CLEARANCE MEASUREMENT SYSTEM HARDWARE

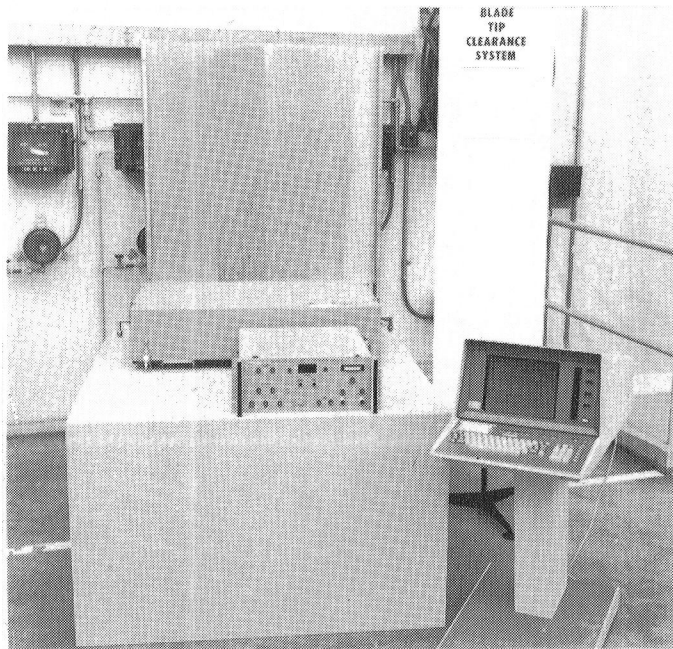


Figure 2

TWO-BEAM SYSTEM USED FOR HOLOGRAPHY AND RELATED
FORMS OF INTERFEROMETRY

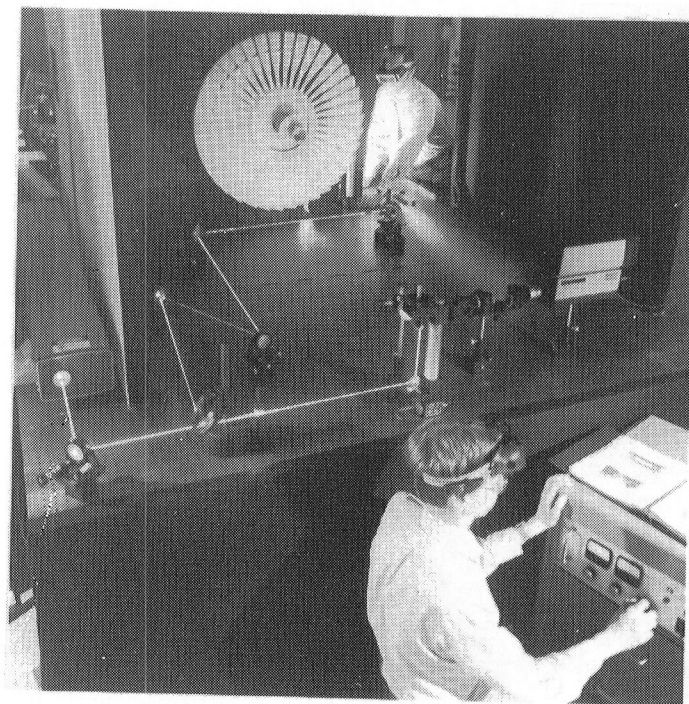


Figure 3

MODAL PATTERN OF A FAN OBTAINED BY TIME-AVERAGE
HOLOGRAPHY

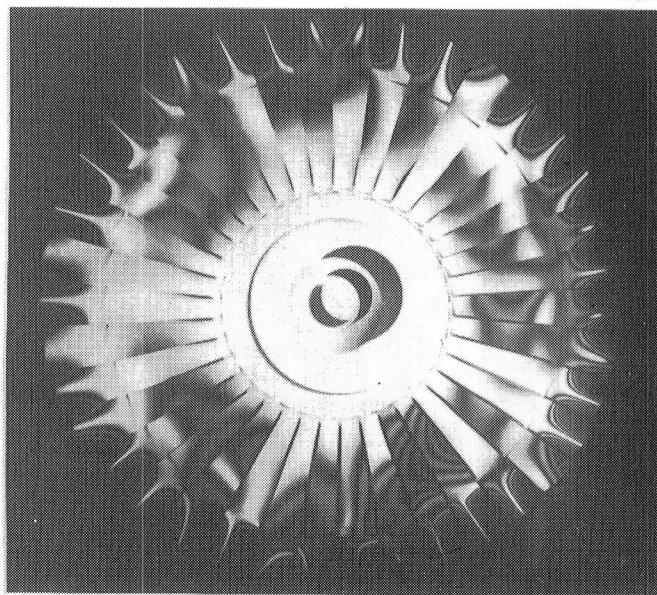


Figure 4

widely applicable for measurement and display of average and single blade tip clearances in turbomachinery over a full range of rotational speeds and for a wide variety of blade materials and configurations.

Holography

One technique usually identified with lasers is holography (ref. 6). In holography, as in other forms of interferometry, two beams of light, object and reference beams, from the same laser (fig. 3) are caused to overlap at a location called the recording plane. The object beam is passed through the object if it is transparent or reflected from the object. The reference beam is chosen to have a simple form so that it can later be easily duplicated. At the recording plane the beams form an alternating light and dark interference pattern that is recorded on a photographic film, forming a hologram. When the hologram is illuminated by the reference beam alone, the object beam is reconstructed and gives a three-dimensional image of any object in the original object beam.

Time-average holography (ref. 7) is an easy-to-use, rapid, definitive, nondestructive method for identifying and displaying natural frequencies and vibrational modes of structures. The structure is forced to vibrate at each of its natural frequencies of interest, and holograms are recorded of the object during several vibration cycles ("time averaging"). Upon reconstruction the three-dimensional image of the vibrating object has superimposed on it the pattern characteristic of the natural mode (fig. 4). The actual distribution of vibration amplitude and regions of maximum stress can be calculated from this pattern.

Similarly, holography can be used to make visible the rapid change in gas density associated with a shock wave, thus allowing it to be visualized in three dimensions (ref. 8). The equipment used to record shock waves in a transonic compressor is shown in figure 5.

HOLOGRAPHY SYSTEM FOR THREE-DIMENSIONAL VISUALIZATION
OF SHOCK WAVES IN A COMPRESSOR RESEARCH FACILITY

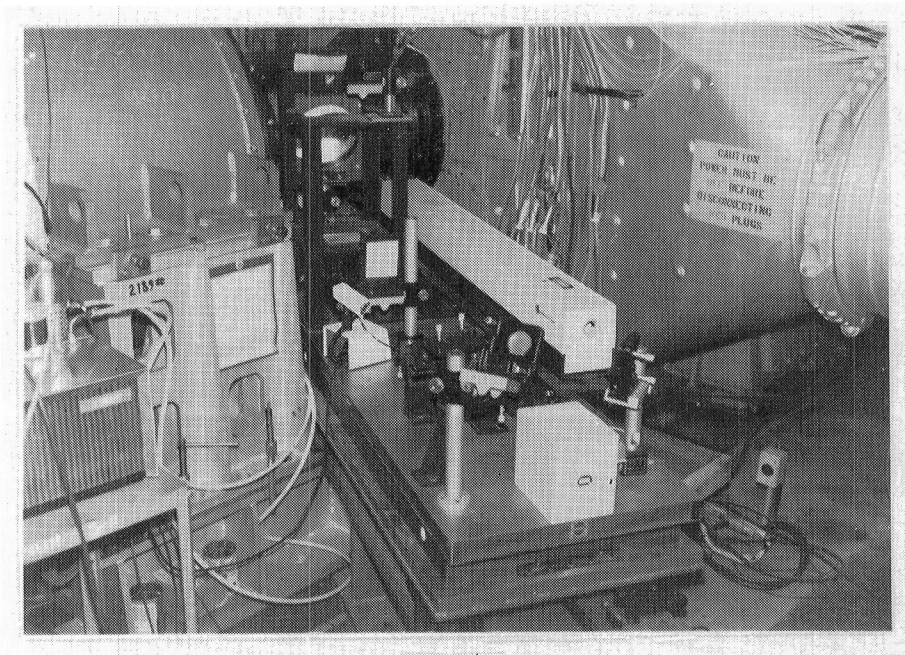


Figure 5

Concluding Remarks

Laser-based measurement systems are costly to buy, operate, and maintain and may require extensive cooling and vibration isolation, but they can make measurements that are impossible with other methods. They provide data and physical insight previously unobtainable at any cost.

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Batteries for Electric Vehicles and Fuel Cells for Efficient Power Generation

J. Stuart Fordyce

Battery Technology

Battery technology can be characterized as near, intermediate, and far term. The range of an electric vehicle is determined by the battery energy storage capacity per unit of weight. The present lead-acid battery, at 10 to 15 Wh/lb, is heavy and expensive and does not offer sufficient range for wide acceptance. Intermediate technologies, nickel-zinc (Ni-Zn) and nickel-iron (Ni-Fe), at 30 to 50 Wh/lb are important for early electric vehicle use. They provide adequate range, and costs appear acceptable if an Ni-Zn cycle life of 300 cycles or more can be achieved and mass production facilities can be established. Nickel-iron is the more robust battery but has charging efficiency problems. Far-term, advanced technologies, at 70 to 100 Wh/lb, operate at high temperatures, and practical development is not certain.

In the Ni-Zn system the separator is a key component. It largely determines battery performance by preventing dendritic shorting and, importantly, by eliminating zinc electrode shape change, thus increasing the cycle life. The Lewis inorganic-organic separator, now being commercialized by the Kimberly Clark Corp., provides substantial improvement over other advanced separators (fig. 1). In large cells and for very deep discharge, cycle life is typically 200 cycles, although General Motors

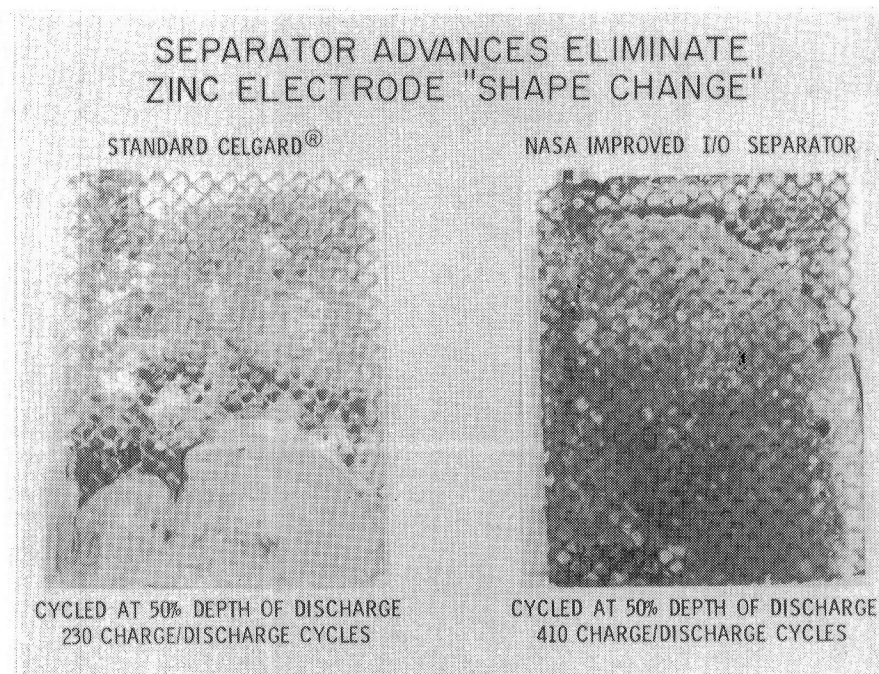


Figure 1

recently achieved 300 cycles. The most recent Lewis development, now being further investigated jointly with W. R. Grace and Co., is a crosslinked polyvinyl alcohol that yields a tough, inexpensive polymer film with the desired separator properties.

Electric Vehicles

An electric vehicle is more energy efficient than an internal combustion engine (ICE) vehicle using either an oil- or coal-based liquid fuel. Under typical urban driving conditions electric vehicles show, on a coal basis, almost twice (11 percent as compared with 6 percent) the efficiency of ICE vehicles and are environmentally benign. A fleet of 25 million electric vehicles by the year 2000 would save up to 400 million barrels of oil per year. This would require about a 1.8 percent increase in electrical generation capacity, which would be easily offset by the load-leveling potential of nighttime recharging.

The usefulness of electric vehicles depends on their ability to meet daily driving needs with an overnight recharge. A Monte Carlo simulation based on driving statistics (fig. 2) shows that a range of 80 miles per day can meet the car owner's needs on 95 percent of the days in a year, or essentially at all times other than long vacation trips. Electric vehicles are most useful as commuter vehicles, with a range between 85 and 100 miles per charge. This range requires appropriate battery technology and proper engineering of the propulsion system, where some improvement can be made. Actual road tests (table I) demonstrate the increased range performance of electric vehicles with the Ni-Zn battery system as compared with a lead-acid battery of equal weight.

Fuel Cells

A fuel cell is an electrochemical device that directly converts gaseous fuel, mostly hydrogen reformed from fossil fuels, and oxygen from air into electricity with the byproducts heat and water

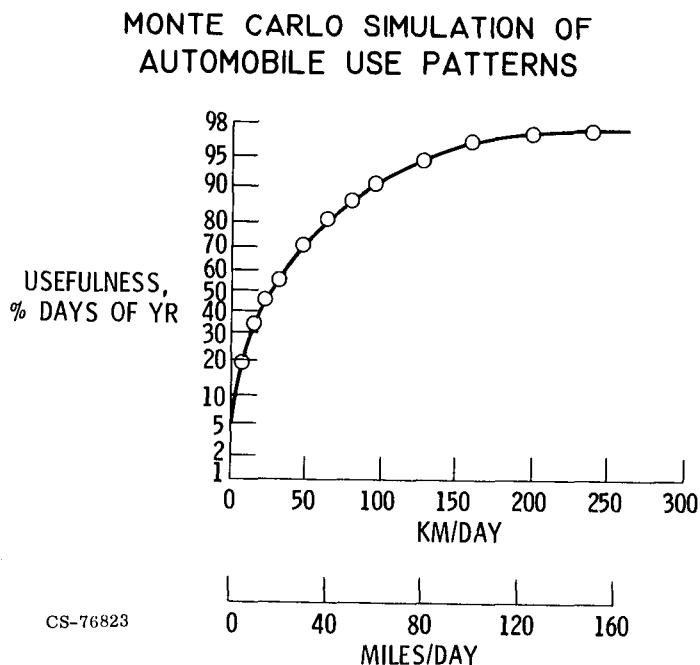


Figure 2

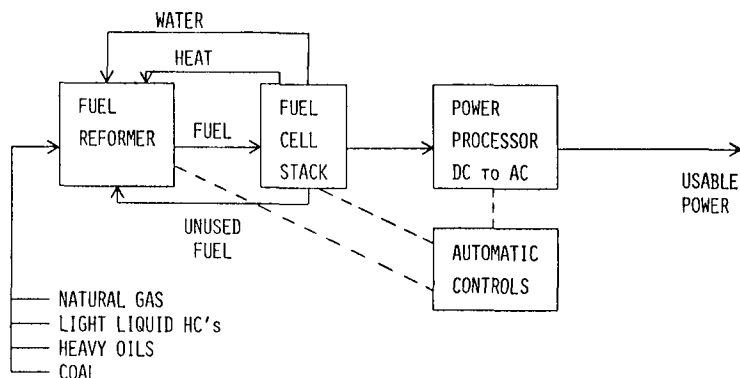
TABLE I.—RESULTS OF NASA ROAD TESTS OF NICKEL-ZINC
POWERED VEHICLES^a

Vehicle	Type of test	Range per charge, miles	Range improvement (over lead-acid batteries), percent
Otis P-500 van	SAE, constant 20 mph	55	+ 97
	SAE, delivery cycle (moderate start-stop)	43	+ 105
	Postal cycle ^b (severe start-stop)	17	+ 75
Copper Development Associates town car	SAE, constant 40 mph	146	+ 83

^aPart of a series of tests performed for ERDA (now DOE) by NASA Lewis reported in NASA TM X-73638 and NASA TM-73756.

^bTest performed by U.S. Postal Service.

WHAT ARE FUEL CELL SYSTEMS?



- AUTOMATIC CONTROLS FOR:
 - HEAT REMOVAL
 - WATER REMOVAL
 - PRESSURE BALANCE
 - STARTUP AND SHUTDOWN SEQUENCES

Figure 3

vapor. Voltages are 1 V dc or less per cell. In a fuel cell system (fig. 3), cells are stacked to the desired voltage level, a reformer processes various fuels to the hydrogen-rich fuel stream, the dc output is converted to ac for the electric service or utility line, and an automatic control system provides programmed operation. Fuel cell systems are efficient (38 percent efficiency for current phosphoric acid and 50 percent for the future molten carbonate) and could save large amounts of fuel in electric utility peaking and load-following service (up to 900 million barrels/yr by the year 2000). Phosphoric acid fuel cell capital costs are still high, but components are now reaching the 40 000-hour endurance goal. Molten carbonate systems are much further behind. United Technologies, Westinghouse, General Electric, Energy Research, Englehard Industries, and others are active in the field, with most

support coming from the Department of Energy (DOE), the Electric Power Research Institute (EPRI), and the Gas Research Institute (GRI). Figure 4 shows a 240-kW dc stack, one of 20 to be combined in a 4.5-MW ac demonstration system on the Consolidated Edison network in New York City, with operation scheduled for early 1981.

Waste heat utilization is possible for any energy conversion system but appears to be very desirable for the fuel cell, which is quiet and nonpolluting and allows "good neighbor" installation in residential, commercial, and industrial areas. Figure 5 shows the energy output split for a typical on-site/integrated energy system (OS/IES); figure 6 illustrates a representative installation. A variety of prototype systems are scheduled to be in operation in the next few years.

240-kW STACK FOR 4.5-MW
DEMONSTRATION SYSTEM

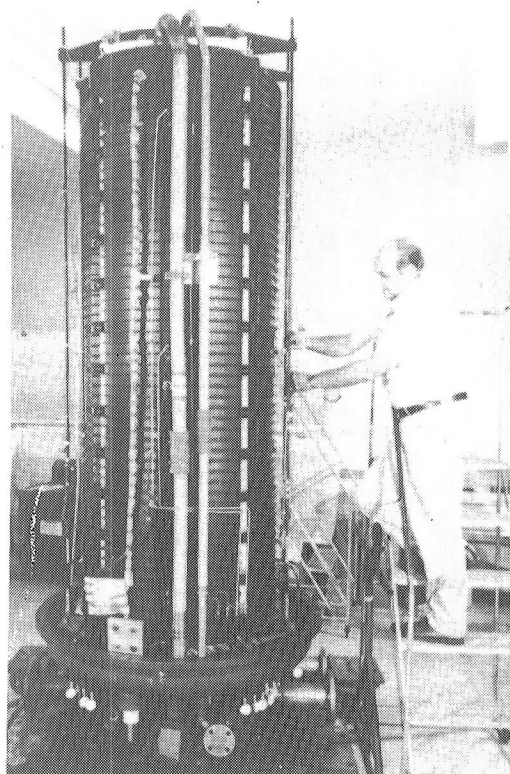


Figure 4

FUEL CELL OS/IES CONCEPT

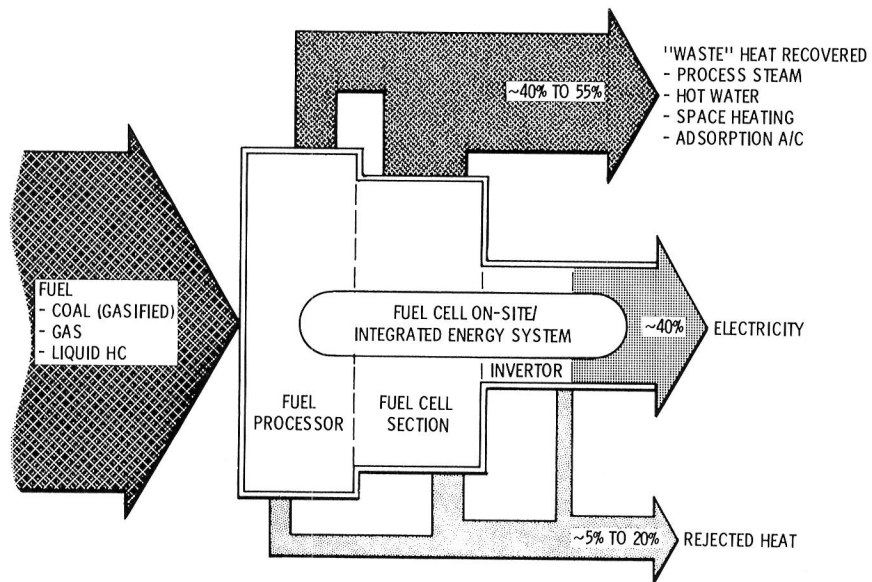


Figure 5

FUEL CELL ON-SITE INTEGRATED ENERGY SYSTEM COMMERCIAL APPLICATION

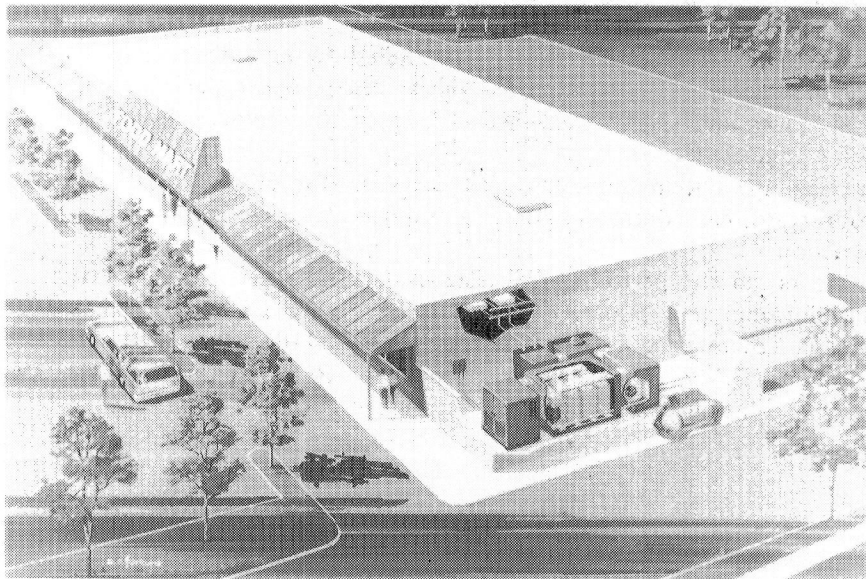


Figure 6

Minicomputers and Microprocessors

Ralph K. Everett

The use of small, inexpensive minicomputers and microcomputers has had a widespread technological effect on many diverse programs at Lewis. To illustrate the power and versatility of these modern devices, some of their applications that have been developed and used at Lewis are briefly described.

Approximately 30 centrally located minicomputers in the Escort data acquisition system support 50 experimental test facilities, some of which are located over one-half mile away. The minicomputers monitor and control testing, check for error conditions, and record data. The interactive control for Escort communication switching is shown in figure 1.

A minicomputer proved to be cost effective in providing automatic control and data processing for pulsed thermocouples. It enabled the thermocouples to accurately measure very high (2200° F) temperatures without being damaged. The operation of a pulsed thermocouple system is shown graphically in figure 2.

An image processing system (fig. 3) produced color pictures representing large volumes of data from scanners on satellites and airplanes, from test facilities, and from theoretical calculations. These data may represent visible light, radar reflections, or physical measurements such as temperature and pressure.

The technique of Fourier spectrum analysis is useful in research and development both as a diagnostic tool and as a means to predict failure. For example, Fourier analysis was used to determine in detail how a helicopter transmission failed during a destructive test (fig. 4).

Because of the microprocessor's high reliability, fast response, light weight, and low cost it is installed in airplanes and spacecraft, where it is used to automatically control complex turbine engines and ion engines (fig. 5).

A pressure scanning system and a gas analysis system (fig. 6) are typical applications illustrating how a microprocessor can control instruments and transducers to record data without the need for manual interaction.

Microprocessors can also perform small tasks as part of a larger system, such as Escort, which is built around minicomputers. Some examples are an interactive control for Escort communication switching (fig. 1), a remote acquisition microprocessor (RAMP), which sends data from each facility to Escort, and a RAMP chassis checkout system. Block diagrams of the operation of the microprocessor and the checkout system are shown in figure 7.

INTERACTIVE CONTROL FOR ESCORT COMMUNICATION SWITCHING

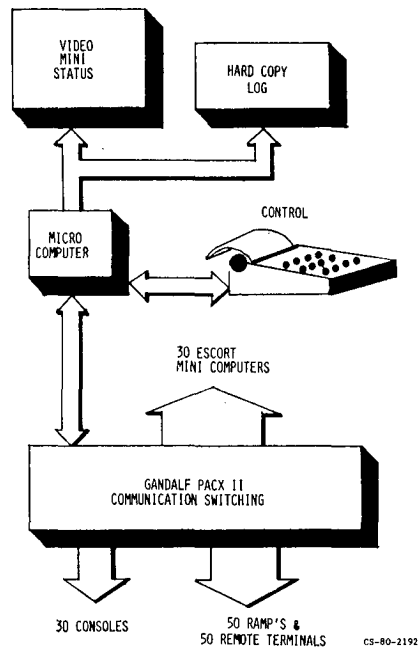


Figure 1

PULSED THERMOCOUPLE SYSTEM

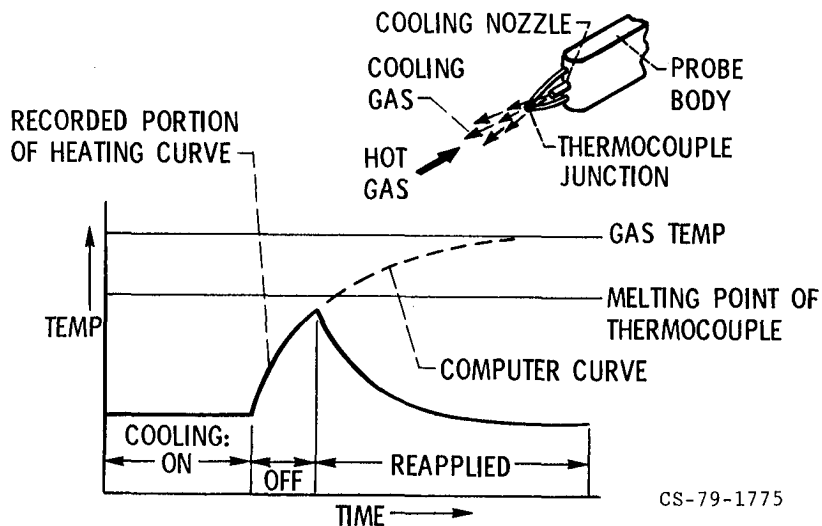


Figure 2

IMAGE PROCESSING SYSTEM

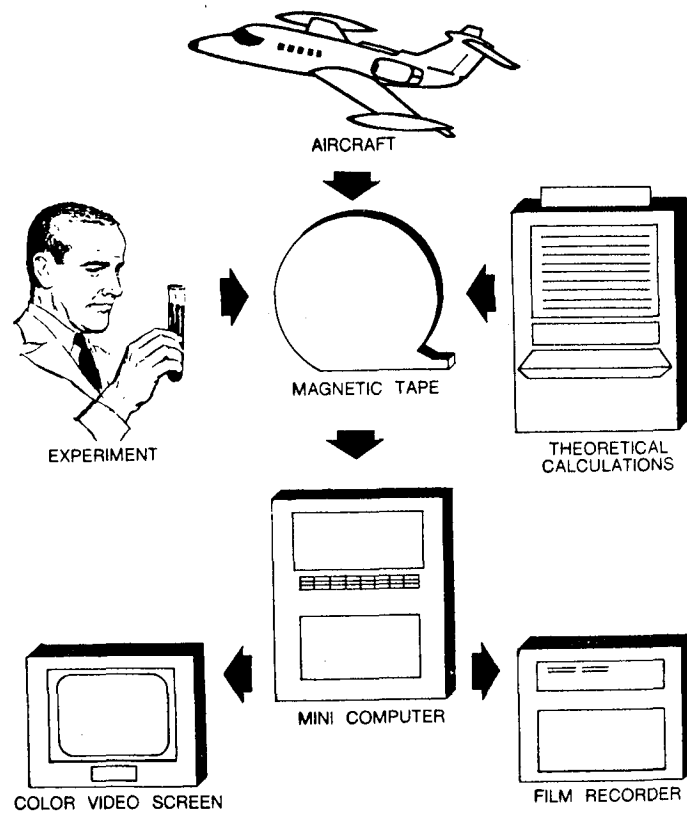


Figure 3

EXAMPLES OF FOURIER SPECTRAL ANALYSES

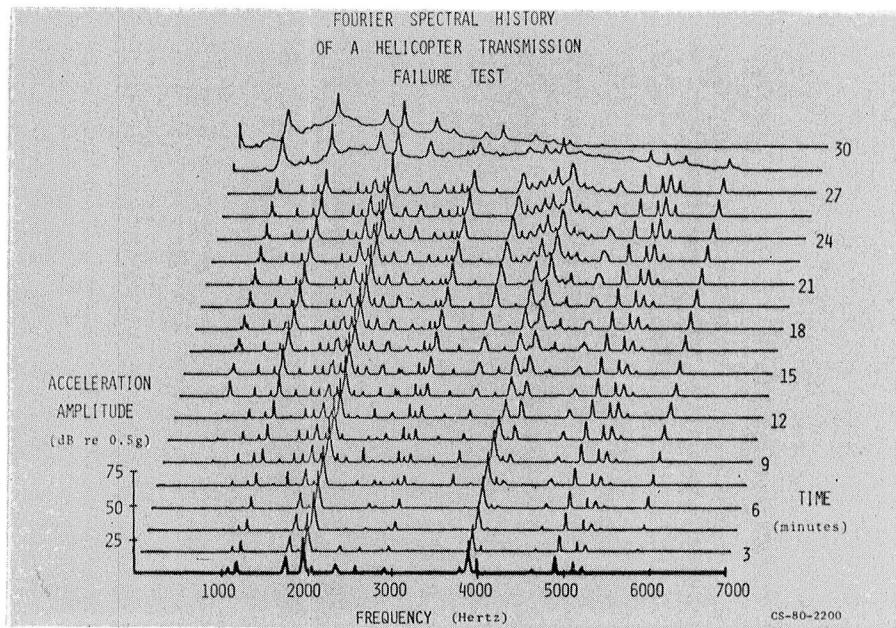
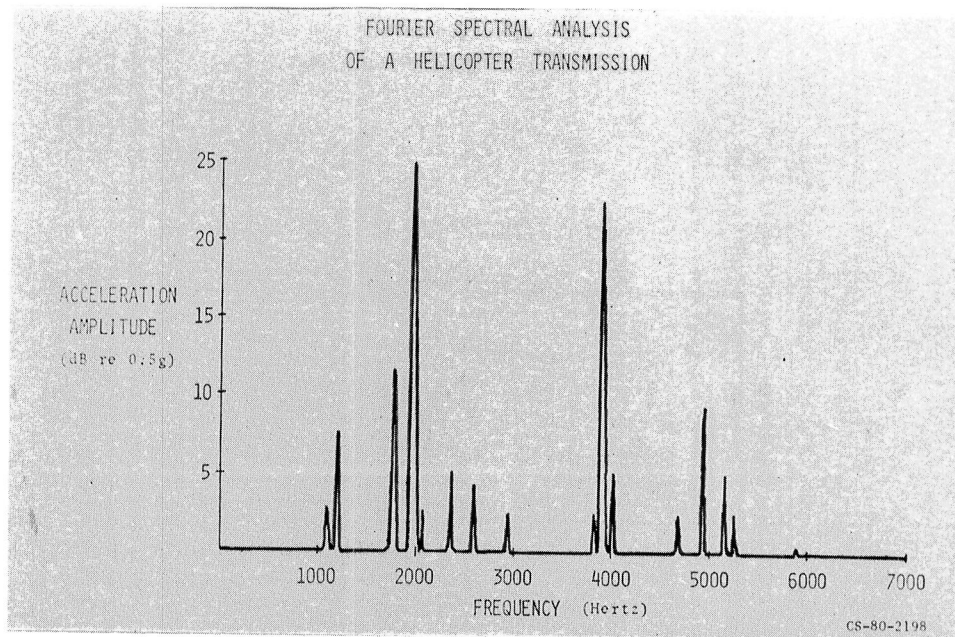


Figure 4

ION ENGINE ENDURANCE TESTING

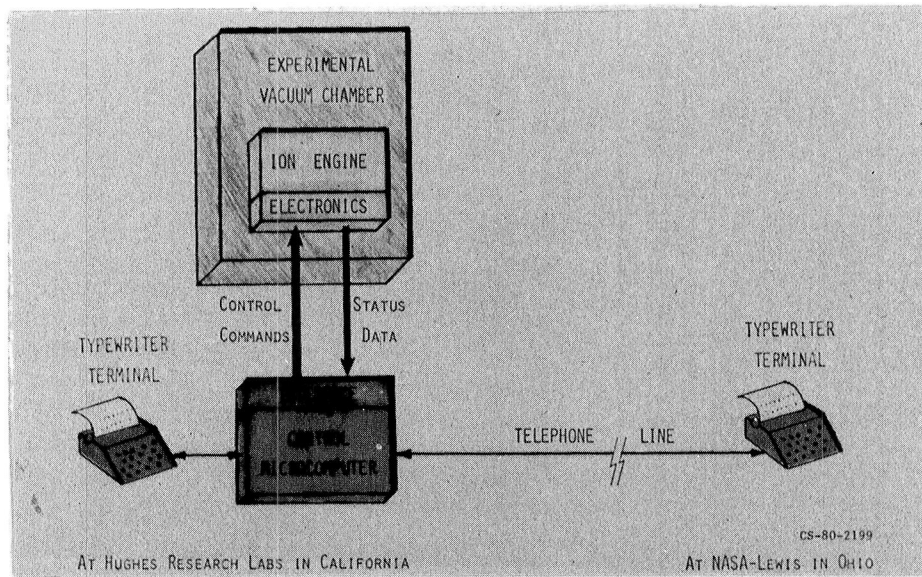
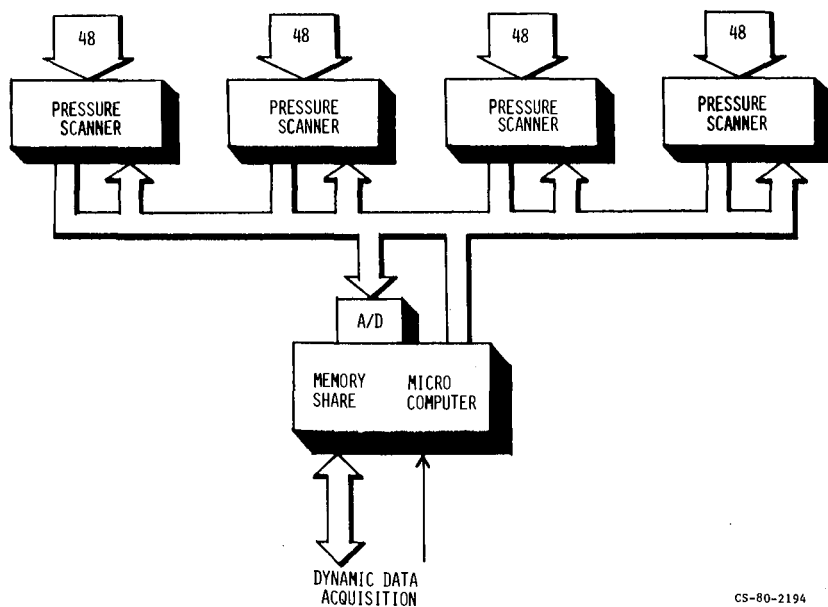
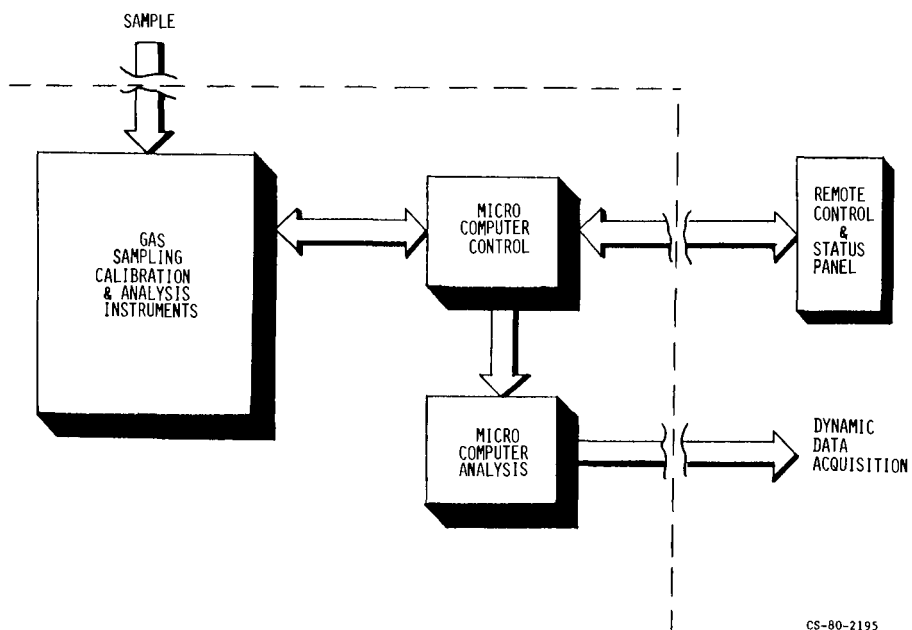


Figure 5

PRESSURE SCANNER AND GAS ANALYSIS SYSTEM



CS-80-2194



CS-80-2195

Figure 6

ESCORT REMOTE ACQUISITION MICROPROCESSOR AND CHASSIS CHECKOUT SYSTEM

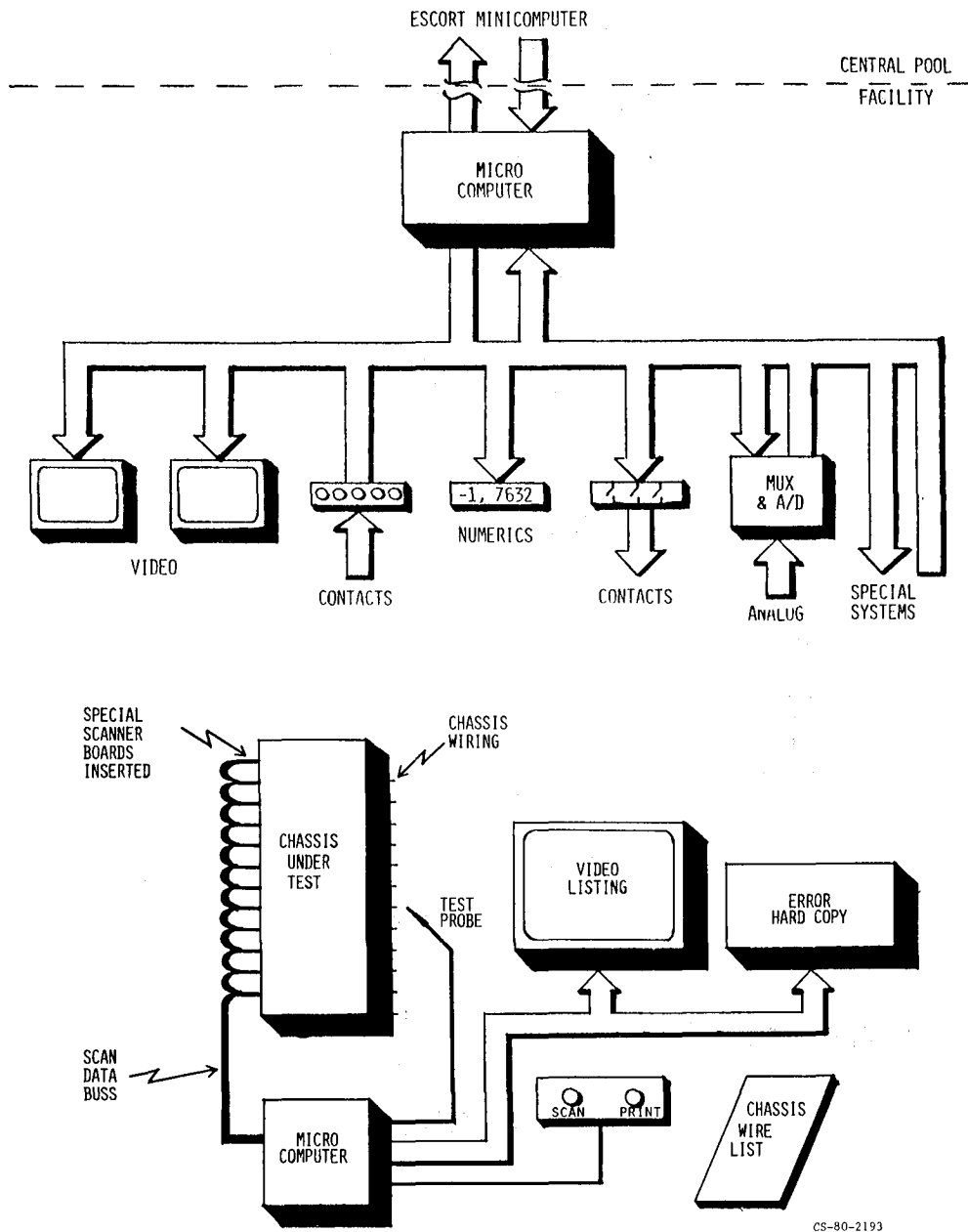


Figure 7

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16. Abstract Aerospace achievements have advanced technology in many areas: electronics, computers, materials, controls, instrumentation, ion beams, bearings, lubrication. This advanced technology has many possible uses outside the space program. Also, aggressive research and technology development in ground-based energy fields - wind power, solar cells, automotive propulsion - hold the promise of both opening new industrial opportunities and significantly affecting existing industry. This Conference was held at the Lewis Research Center, Cleveland, Ohio, on May 14 and 15, 1980, to provide briefings in selected broad technology areas and on specific items of particular note. It furnished information believed to be of substantial interest and potential value. Subjects covered were ground-based energy (an overview), aircraft propulsion (an overview), wind power commercialization, materials and structures, lubrication and bearings, Stirling and gas turbine engines, electric and hybrid vehicles, coal gasification and co-generation, solar photovoltaics, materials processing in space, and technology transfer. Field stops were ion beam applications, magnetic heat pump, long-life cathode and traveling wave tube, multiroller traction drive, general-aviation aircraft engines, redox, laser applications, advanced battery systems, and minicomputers and microprocessors. An evening talk by the Chairman of the Board of the Eaton Corporation is included in the proceedings.			
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